NASA CR-135417

DESIGN OF IMPACT-RESISTANT BORON/ALUMINUM LARGE FAN BLADES

July 1978

by

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GENERAL ELECTRIC COMPANY

(NASA-CR-135417) DESIGN OF IMPACT-RESISTANT BORON/ALUMINUM LARGE FAN BLADE (General Electric Co.) 93 p HC A05/MF A01 CSCL 21E

N78-29104

Unclas

G3/07 28521

Prepared For

National Aeronautics and Space Administration

NASA Lewis Research Center
NAS3-21041

1. Report No. NASA CR-135417	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle DESIGN OF IMPACT-RESISTANT BORON/ALUMINUM LARGE FAN BLADE		5. Report Date July 1978
		6. Performing Organization Code
7. Author(s) C.T. Salemme, S.A. Yokel		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address General Electric Company 1 Neumann Way Cincinnati, Ohio 45215		11. Contract or Grant No. NAS3-21041
		13. Type of Report and Period Covered Contractor Report
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes Project Manager, David L. McDanels NASA-Lewis Research Center Cleveland, Ohio 44135		

16. Abstract

This report describes the results of a six-month program beginning in October, 1977 designated to design all impact-resistant boron/aluminum large fan blades with proper aeromechanical characteristics.

The technical program was comprised of two technical tasks. Task I encompassed the preliminary boron/aluminum fan blade design effort. Two preliminary designs were evolved. An initial design consisted of 32 blades per stage and was based on material properties extracted from manufactured blades. A final design of 36 blades per stage was based on rule-of-mixture material properties.

In Task II, the selected preliminary blade design was refined via more sophisticated analytical tools. Detailed finite element stress analysis and aero performance analysis were carried out to determine blade material frequencies and directional stresses.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Composite blades Fan blades Boron/aluminum composite Aluminum	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	73	

* For sale by the National Technical Information Service, Springfield, Virginia 22151

NASA-C-168 (Rev. 6-71)

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Engineering Masters	Accurately delineates, undimensioned, drawings on dimensionally stable material.
Reduced Velocity	A measure of a blades stability against self-excited vibration. This ratio is defined as V_R = W/b f_t where b = ½ chord at 5/16 span, W = average air velocity relative to the blade over outer third of the span and f_t = first torsional frequency at design rpm.
Normal Design	Steady-state mechanical design with full stage of blades in the disk -- 4080 rpm.
Blade-Out	A full stage of blades less one blade -- this condition caused bending of the free disk post.
Disk Post	Support shank of the disk dovetail -- a full stage disk has same number of disk posts as number of blades.
Post-Neck	Thinnest part of disk post where blade-out bending is calculated.
Started Flow	Attached oblique wave

1.0 SUMMARY

Resin and metal matrix composites are recognized as having significant potential as replacement materials for titanium fan and compressor blade applications. For example, substantial cost and weight reduction benefits, on the order of 25%, have been projected for the CF6 fan with the use of composite materials. Heretofore, the lace of foreign object damage (FOD) resistance such as large bird ingestion has been a major deterrent to the use of composites for large fan blade application. Recently, however, significant improvement in impact resistance of 0.02 cm (8 mil) boron/1100 aluminum composite materials has been achieved. Recognizing the signficance of this recent development, NASA sponsored a program at General Electric under Contract NAS3-19729 in late 1975 in conjunction with TRW to evaluate the impact performance of boron/aluminum and fabricate large fan blades using the boron/aluminum material. The work under this program was completed in 1976 with the manufacture of two prototype CF6 boron aluminum fan blades. The current program reported herein is a follow-on effort under Contract NAS3-21041 which was initiated in October, 1977 with the objective of designing an aeromechanically acceptable CF6 boron/aluminum blade. This work was completed in two technical tasks as shown in the flow diagram of Figure 1 over a seven-month period of performance. Task I was comprised of the preliminary mechanical and aerodynamic design of the blade, with the primary emphasis being placed on the selection of the number of blades in the fan stage and the initial blade geometry. In Task II, the preliminary design selected from Task I was refined and detailed drawings made. The design refinements included detailed aerodynamic design analysis to finalize the blade geometry and estimate its aerodynamic performance. Detailed structural analysis was performed using three dimensional finite element analysis models to determine the blade stresses, deflections and natural frequency characteristics.

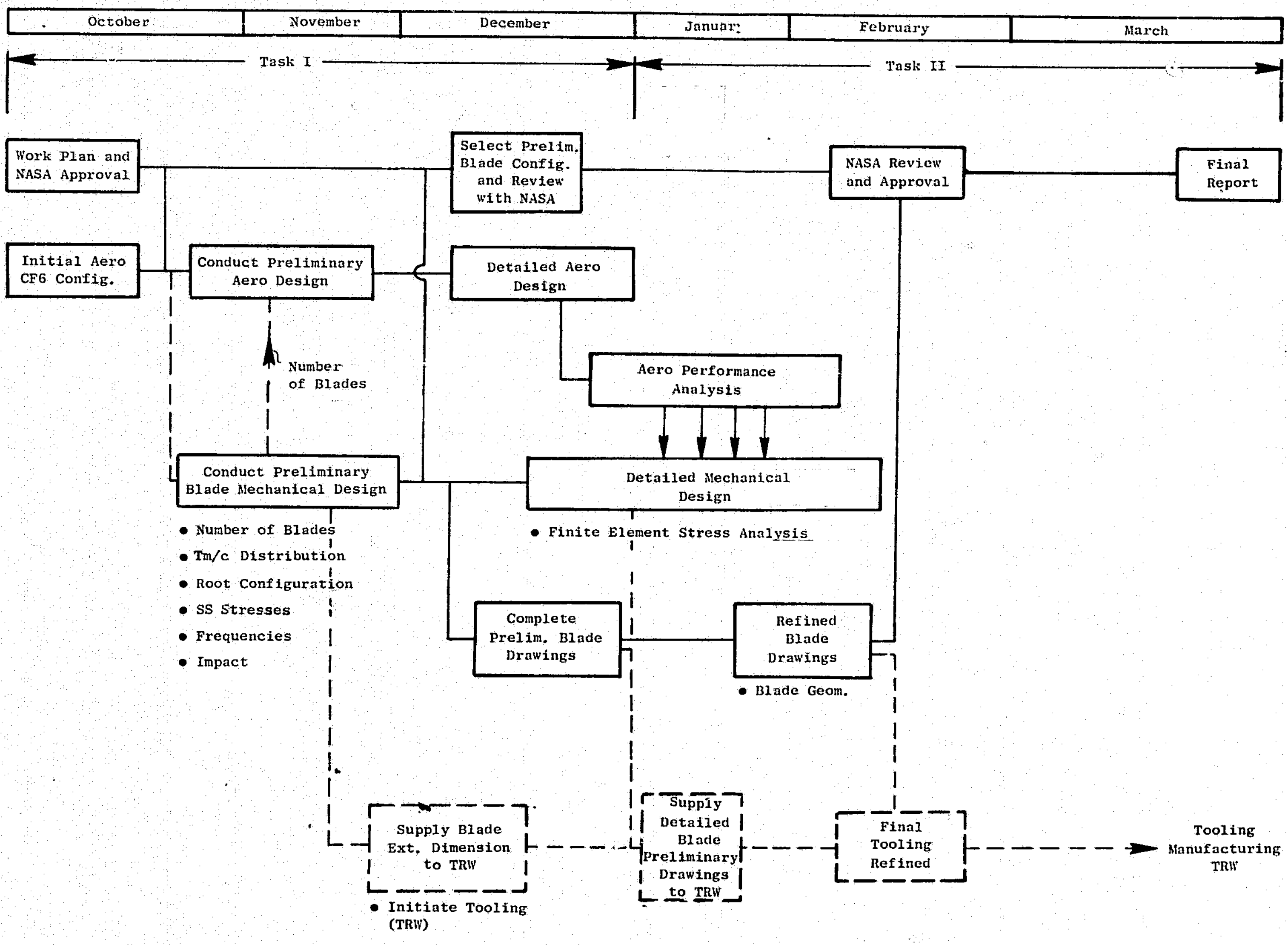

Figure 1. NASA Large B/Al Blade Program.

2.0 INTRODUCTION

During the past two years the development of large boron aluminum fan blades has been directed toward the evaluation of fabrication feasibility and FOD resistance. For these evaluations the existing CF6-50 titanium fan blade design has been used with the elimination of the midspan shroud. This direct substitution was made to reduce cost by using existing CF6 blade tooling and to demonstrate fabrication feasiblity, assess blade natural frequency characteristics and FOD resistance of the B/Al blade relative to a metal blade of the same configuration.

Work recently completed under NASA sponsorship (NAS3-19729) utilizing the CF6 blade configuration for the fabrication of a B/Al composite blade has demonstrated fabrication feasibility. First torsional blade frequency of the fabrication demonstration CF6 B/Al blade was higher than that of an unshrouded metal blade but not as high as a shrouded titanium CF6-50 fan blade. Thus, the aeromechanical flutter characteristics of the B/Al blade are not acceptable from an engine operational standpoint. This means that a complete blade redesign is required to provide a blade which meets mechanical, aeromechanical and aeroperformance requirements of the CF6 engine.

The objective of this program was to design an unshrouded B/Al fan blade consistent with the aerodynamic size of the CF6 metal blade but being of lower number of blades per stage to achieve engine aeromechanical acceptability. This six month program was comprised of two technical tasks and a reporting task. Each of the two technical tasks were three months in duration. Task I was a preliminary blade design effort and Task II was the detailed blade design.

During the conduct of the program, design drawings were supplied to NASA at three stages. The initial drawing was an engineering sketch containing the best estimate of blade external plan view dimensions six weeks after inception of the program. This initial blade definition allowed the ordering of the long lead time die stock material. At the completion of Task I, a complete set of preliminary blade drawings was supplied to NASA including engineering masters of 22 airfoil radial sections. After 4-1/2 months of effort, a complete set of detailed drawings were supplied to NASA which reflected refinements in the preliminary aeromechanical design. These refinements are minor blade modifications in blade shape in the areas of leading edge and root transition which have a significant effect on the overall performance of the blade.

Task I of the program was the preliminary B/Al blade design effort. The initial blade aerodynamic configuration utilized at the start of this task was that of the 38-blade CF6 and 24-blade F103 first stage fan appropriately scaled for the number of blades which was updated periodically to reflect preliminary aeromechanical studies, i.e., changes in camber, twist, thickness, tm/c, etc.

In Task II the selected preliminary blade design was refined based on more sophisticated analytical efforts which included finite element stress analysis and aerodynamic performance analysis. These analysis were carried out to calculate blade natural frequencies and directional stresses and margins of safety for steady state operating conditions. Blade design weight and aerodynamic payoffs were determined relative to the CF6-50 titanium production blade design. The blade geometry, material selection and B/Al ply orientation were finalized in this task.

3.0 PRELIMINARY/BLADE DESIGN

3.1 BASELINE BLADE AERO DESIGN

Detailed aerodynamic designs had been previously made for the CF6 fan blade. One design, a 38 blade design is the current production configuration and a 24 blade design for a graphite/epoxy development fan blade defined as the F103 blade design. Figure 2 shows the airfoil geometric parameters for these two designs. Note that the solidity parameter for both designs was held constant at each airfoil radial section. The solidity parameter is defined as

$$\text{Solidity, } S = \frac{CN}{2\pi R}$$

where C is the airfoil chord length, N is the number of blades in the stage and R is the radius. Also note that there is very little change in blade camber and stagger in these designs. These three parameters are primary airfoil aerodynamic efficiency determining parameters which were held constant during the aeromechanical sizing of the B/Al fan blade parametric design studies.

In Task II, detailed aerodynamic analysis were carried out to identify the airfoil camber and stagger angles for the B/Al blade design selected. In addition, aerodynamic efficiency estimates were made for this new design.

3.2 PARAMETRIC BLADE STUDY

3.2.1 Initial Blade Geometry

Preliminary estimates from previous work indicated a good starting point to be 28 to 30 blades per stage, scaled from the F103 aero design (unshrouded CF6 aero design). The highest number of blades possible was finally arrived at consistent with the aeromechanical and FOD requirements. Maximum thickness to chord ratio (tm/c) for the initial blade configuration was 12.0% at the inner flowpath and 3.1% at the outer flowpath with an almost linear distribution between. Blade leading-edge thickness to chord ratio (tm/c) was increased over that of the original F103 blade design for impact improvement. Inner flowpath increase was from 1.8% to 2.4% and outer flowpath increase was from 0.5% to 1.0%.

3.2.2 Baseline Material Properties

Material property estimates were generated and evaluated from several sources; rule of mixtures for 50% and 55% boron volume fraction, direct substitution CF6 blade manufactured by TRW (NAS3-19729), and two blades manufactured by General Electric. Using frequency data from TRW's CF6 and

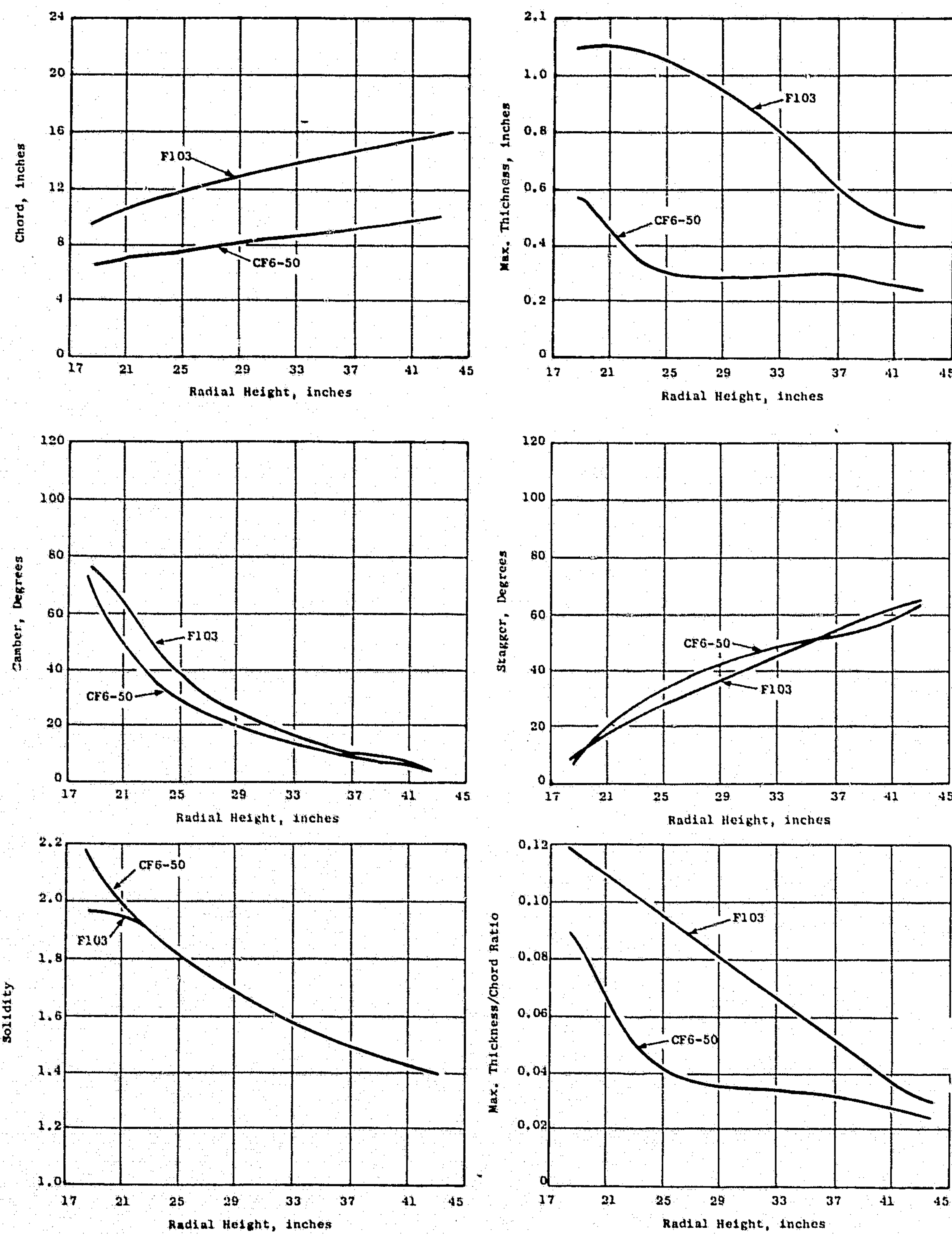

Figure 2. Comparison of CF6-50 Titanium and F103 Polymeric Composite Blade Geometry.

GE's J79 and J101 boron/aluminum fan blades in conjunction with existing analytical models, estimates for material properties were determined. The material system used in TRW's CF6 blade was a 50% boron volume fraction at a ±30° ply orientation skin and ±15° ply orientation core. GE's J79 blade material system was a 50% boron volume fraction at a ±15° ply orientation while the J101 blade was a 55% boron volume fraction at a ±15° ply orientation. Table I lists the materials properties determined from existing blades and rule of mixture.

The various material property estimates were evaluated during the preliminary design task via parametric studies. The design studies using properties from blade data were judged somewhat pessimistic in that the material properties used were based on a small number of manufactured blades. Material properties selected after much discussion with NASA and TRW relative to what was thought to be achievable in large boron/aluminum blades were the rule of mixture properties for 8 mil diameter 55% boron volume fraction boron/ aluminum material at a ±15° ply orientation. NASA was in concurrence with this selection, recommending that the blade airfoil be 1100 aluminum and dovetail region be 6061 aluminum.

3.2.3 Preliminary Blade Analysis Method

A time-sharing twisted blade program has been developed for preliminary analysis of composite fan blades. This uncoupled twisted blade/beam-type analysis uses homogeneous material properties and assumes a blade biconvex airfoil configuration. The program requires a minimal of blade geometry inputs, i.e., camber, twist, chord, maximum thickness to chord ratio and leading edge thickness to chord ratio values for airfoil sections. Program output is weight, centrifugal stress, natural frequencies, and reduced velocity parameter. This analytical data has been calibrated for composite materials via blade test data.

By varying maximum thickness/chord distributions and changing chord to represent change in the number of blades, parametric studies of different blade designs are compared to a baseline, Table II. Figure 3 shows the various tm/c distributions evaluated for the CF6/F103 boron/aluminum fan blade before finding an initial preliminary 32 blade design. Studies ranged from 28 blades per stage to 38 blades per stage. (The original F103 polymeric composite design is 24 blades per stage and the original CF6 titanium design is 38 blades per stage.)

Two studies were carried out: one using the material properties determined from the TRW CF6 blade and the second using the rule of mixture material properties. The purpose of these studies was to identify the effect of material properties on the blade geometry requirements.

Blade weight and stage weight without taking into consideration of platform weight for a range of tm/c distributions and different numbers of blades per stage are represented in Figure 4 by indicating the extremities of

Table I. Material Property Evaluation.

Source	Fiber Volume	Ply Orientation	$E \times 10^6$ psi	$G \times 10^6$ psi
CF6 TRW Blade	50%	±15	24.7	6.4
	50%	±30	19.0	7.2
J79 GE Blade	50%	±15	24.9	5.8
J101 GE Blade	55%	±15	33.0	7.0
Rule of Mixture	50%	±15	32.1	7.6
	50%	±30	24.7	8.6
Rule of Mixture	55%	±15	35.0	9.5

Table II. Parametric Study Matrix.

	CF6 B/Al W/LR Increased →				F103 B/Al W/LR Increased →			F103 B/Al W/LR Increased →			F103 B/Al W/LR Increased 90% F103 tm/C	F103 B/Al W/LR Increased 80% F103 tm/C	F103 B/Al W/LR Increased K³ tm/C	F103 B/Al W/LR Increased 90% F103 tm/C at Tip 95% F103 tm/C at Root	F103 B/Al W/LR Increased 90% F103 tm/C at Tip 95% F103 tm/C at Root	F103 B/Al W/LR Increased →			F103 B/Al W/LR Increased 90% F103 tm/C	F103 B/Al W/LR Increased 80% F103 tm/C	F103 B/Al W/LR Increased 90% F103 tm/C	F103 B/Al W/LR Increased 80% F103 tm/C	F103 B/Al W/LR Increased 91% F103 tm/C
I Flex at Zero	30.1	34.7	40.7	48.2	40.6	47.1	55.0	45.8	49.5	53.7	52.1	48.6	54.1	54.7	65.0	57.8	62.2	67.0	54.3	50.9	58.6	54.9	50.6
I Torsional at Zero	187.4	192.4	199.7	211.5	366.3	366.1	362.9	423.3	422.2	422.7	336.3	302.8	355.5	352.8	433.1	451.5	451.7	453.4	409.9	367.6	410.6	368.6	410.1
I Flex at Speed	87.9	94.2	94.8	100.0	91.2	96.4	103.4	94.6	97.6	101.1	99.7	95.6	102.3	98.9	109.1	103.7	107.3	111.3	100.0	96.3	103.4	99.5	94.6
I Torsional at Speed	213.8	216.8	222.2	232.0	378.3	377.4	379.5	438.2	436.7	436.7	347.8	315.6	366.8	368.1	445.8	464.2	464.1	465.5	423.9	383.2	424.1	383.7	423.8
Reduced Velocity	2.9	2.5	2.2	1.8	1.6	1.5	1.3	1.3	1.3	1.2	1.4	1.5	1.3	1.4	1.2	1.2	1.2	1.1	1.7	1.5	1.3	1.4	1.4
2/rev Crossover	30%	34%	40%	47%	34%	39%	47%	40%	45%	50%	49%	48%	50%	50%	—	—	—	—	50%	47%	52%	50%	48%
Blade Weight	6.7	8.3	10.6	14.0	9.5	11.8	15.1	10.6	11.8	13.3	13.8	12.5	14.8	13.2	13.2	10.9	12.3	13.9	10.0	9.0	11.2	10.1	9.7
Stage Weight	254.6	282.2	318.0	364.0	361.0	401.2	453.0	381.6	401.2	425.6	414.9	376.2	444.0	422.4	422.4	392.4	418.2	444.8	360.0	324.0	380.8	343.4	349.9
σ_{max} (Avg) ksi	31.5	31.3	30.9	30.6	34.9	34.7	34.5	34.2	34.2	34.0	34.3	34.8	33.1	31.0	31.0	31.0	31.0	31.0	31.1	31.2	31.1	31.2	31.1
σ_{root} (Avg) ksi	22.3	22.2	21.9	21.7	34.9	34.7	34.5	34.2	34.2	34.0	34.3	34.8	33.1	28.0	28.0	28.0	28.0	28.0	28.2	28.4	28.1	28.3	28.0
F_C Root klb	79.5	98.7	124.8	164.8	116.5	144.9	185.4	129.8	144.9	163.0	169.3	153.4	180.6	155.3	155.3	128.4	144.1	162.6	116.9	105.5	131.3	118.4	115.9
Tensile Modulus	Shell 19.0 Core 24.7	→	→	→	→	→	→	Shell 24.7 Core 32.1	→	→	Shell 19.0 Core 24.7	→	→	24.7	35.0	→	→	→	→	→	→	→	→
Shear Modulus	Shell 7.2 Core 6.3	→	→	→	→	→	→	Shell 8.6 Core 7.6	→	→	Shell 7.2 Core 6.3	→	→	6.3	9.3	→	→	→	→	→	→	→	→
Fiber Volume	50%	→	→	→	→	→	→	50%	→	→	50%	→	→	50%	55%	→	→	→	→	→	→	→	→
Number of Blds	38	34	30	26	38	34	30	36	34	32	30	30	30	32	32	36	34	32	36	36	34	34	36

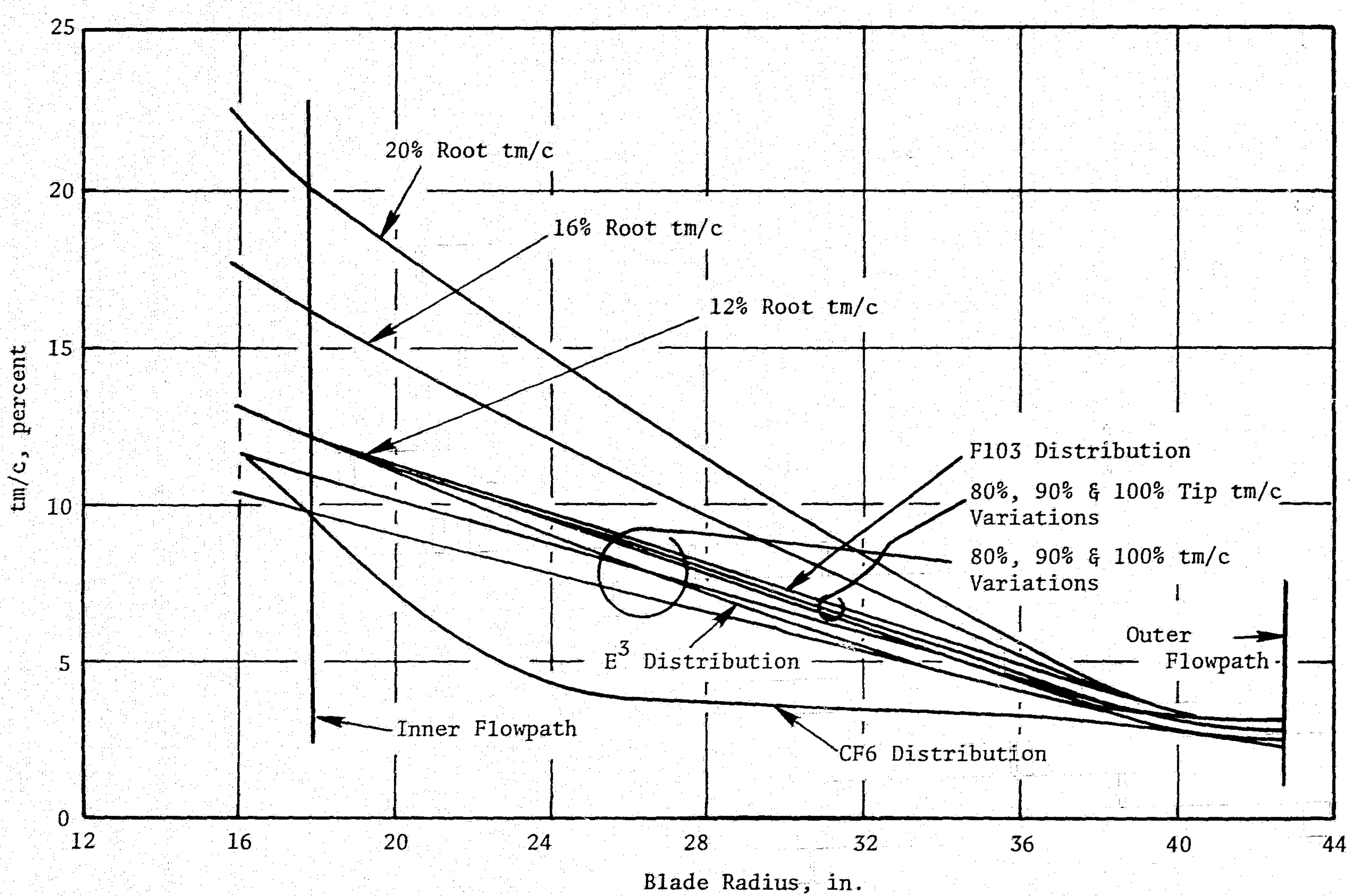

Figure 3. Maximum Thickness/Chord Distributions.

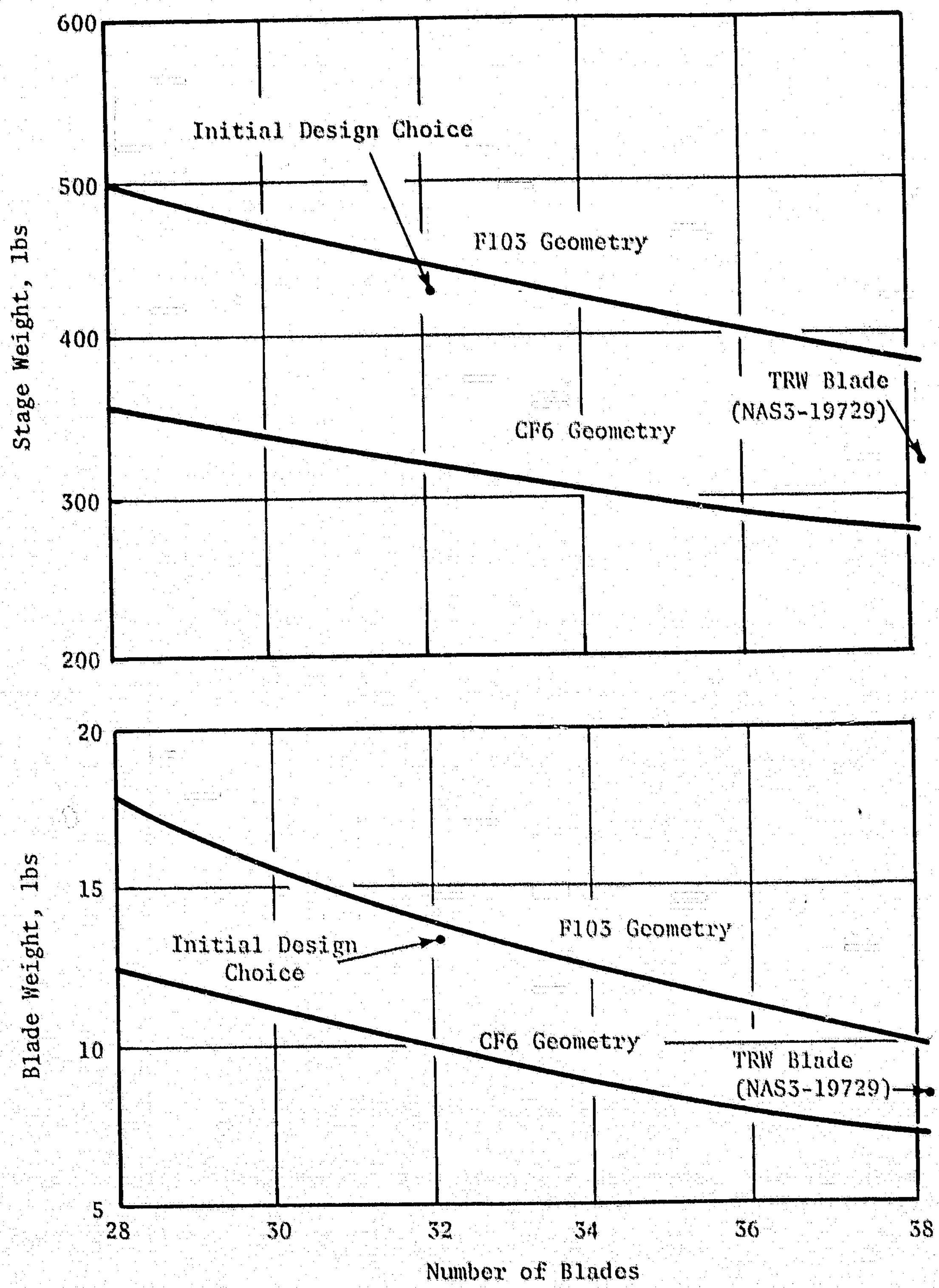

Figure 4. Parametric Study Blade and Stage Weights (Without Platform Weight).

tm/c distributions. These results were based on TRW CF6 blade material property estimates. CF6 thickness to chord distributions are less than F103 distributions as indicated in Figure 3. The initial design choice (32 blades per stage) and the TRW CF6 direct substitution baseline design are shown to indicate their respective positions in the weight summary (Figure 4). The 32 blade design indicates a blade weight without platform of 13.2 pounds and a stage weight of 424.4 pounds. Adding a 0.5 pound platform gives a 13.7 pound blade and 438.4 pound blade stage which is 20.4 pounds heavier than the CF6 titanium design at 418 pounds for the blade stage.

Using the rule of mixture boron/aluminum material properties, a 36 blade per stage design was conceived. Figure 5 shows this blade design weight, blade stage weight, and maximum thickness as a function of percent reduction in tm/c distribution relative to the original F103 design. Using this material system as agreed upon by NASA, a 36 blade design having a tm/c distribution of 91% of the original F103 satisfies the aeromechanical stability requirements. Blade weight including platform is 10.22 pounds which is a 367.92 pound blade stage. This is 50.08 pounds lighter than the CF6 titanium design.

As can be seen from Table II, the material properties values have a strong influence on the blade geometry. The 36 blade design was selected for detail design in Task II. This selection was approved by NASA.

3.2.4 Frequency Characteristics

Using the initial baseline materials generated from TRW's CF6 direct substitution fan blade while varying geometry between CF6 and F103 blade characteristics generated a band of reduced velocity and two-per-rev crossover parameters versus number of blades. Figure 6 shows this variation in reduced velocity and two-per-rev crossover for a cantilevered boron/aluminum blade design ranging from 28 blades to 38 blades per fan stage. As the maximum thickness to chord ratio increased going from the CF6 geometry to F103 geometry, the potential to satisfy reduced velocity requirements also increases for the same number of blades. The reduced velocity goal is 1.4 or less. Initial design choice indicated on Figure 6 represents an F103 tm/c distribution that is 95% of the original F103 design at the inner flowpath and 90% at the outer flowpath. Reduced velocity is 1.34 using initial baseline materials from TRW's CF6 B/Al fan blade.

Frequencies of interest for blade stability characteristics are indicated on the Campbell diagram, Figure 7. First flex crosses two-per-rev at 50% speed with its range being 54 cps at zero rpm and 99 cps at 3950 rpm. First torsion ranges from 355 cps at zero rpm to 369 cps at 3950 rpm producing the aeromechanical stability limit of 1.39.

Using the material property system agreed upon by NASA to complete the parametric study resulted in a 36 blade design with a tm/c distribution of 91% of the original F103 design. This design produced a reduce velocity

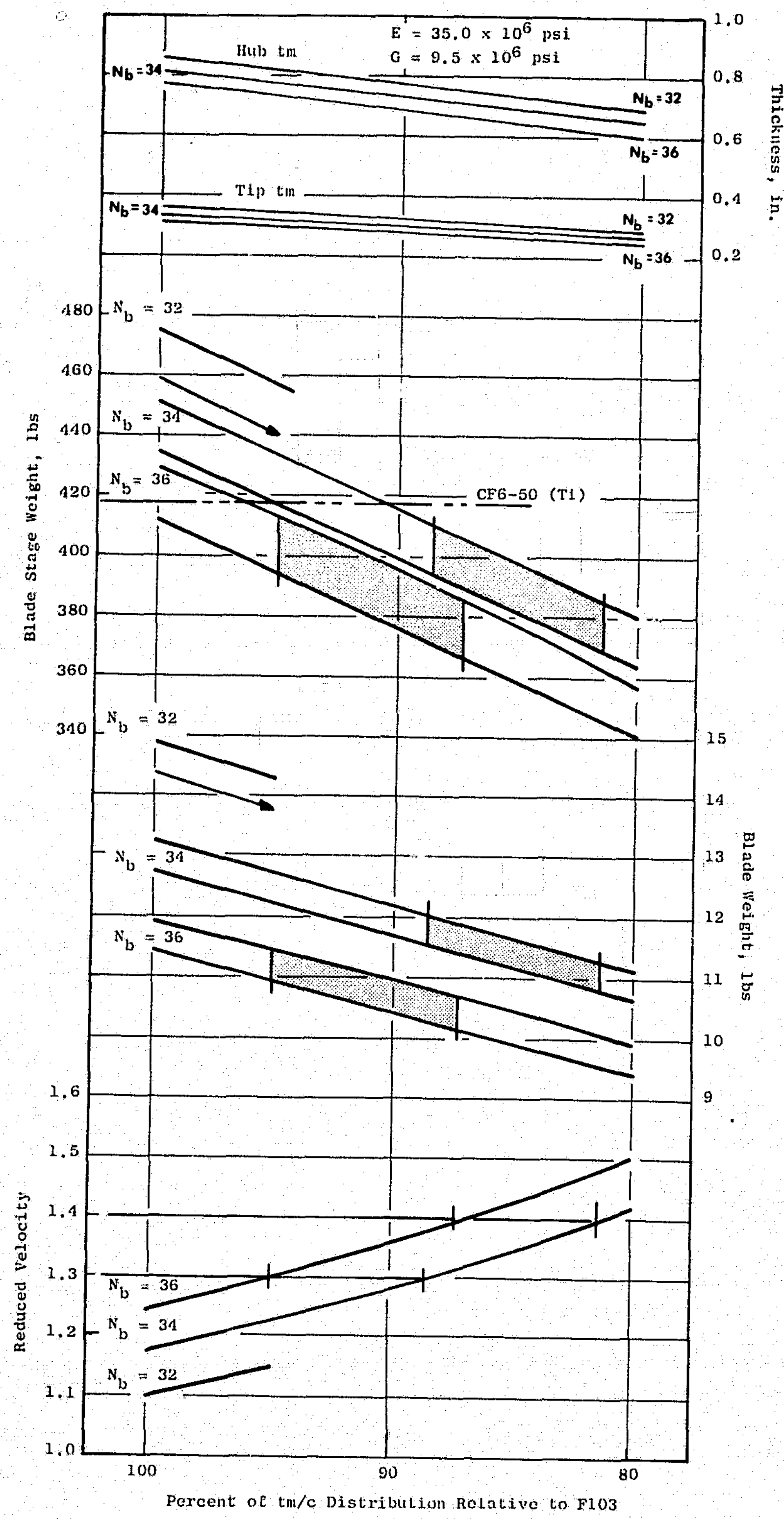

Figure 5. Large B/Al Fan Blade Parametric Study.

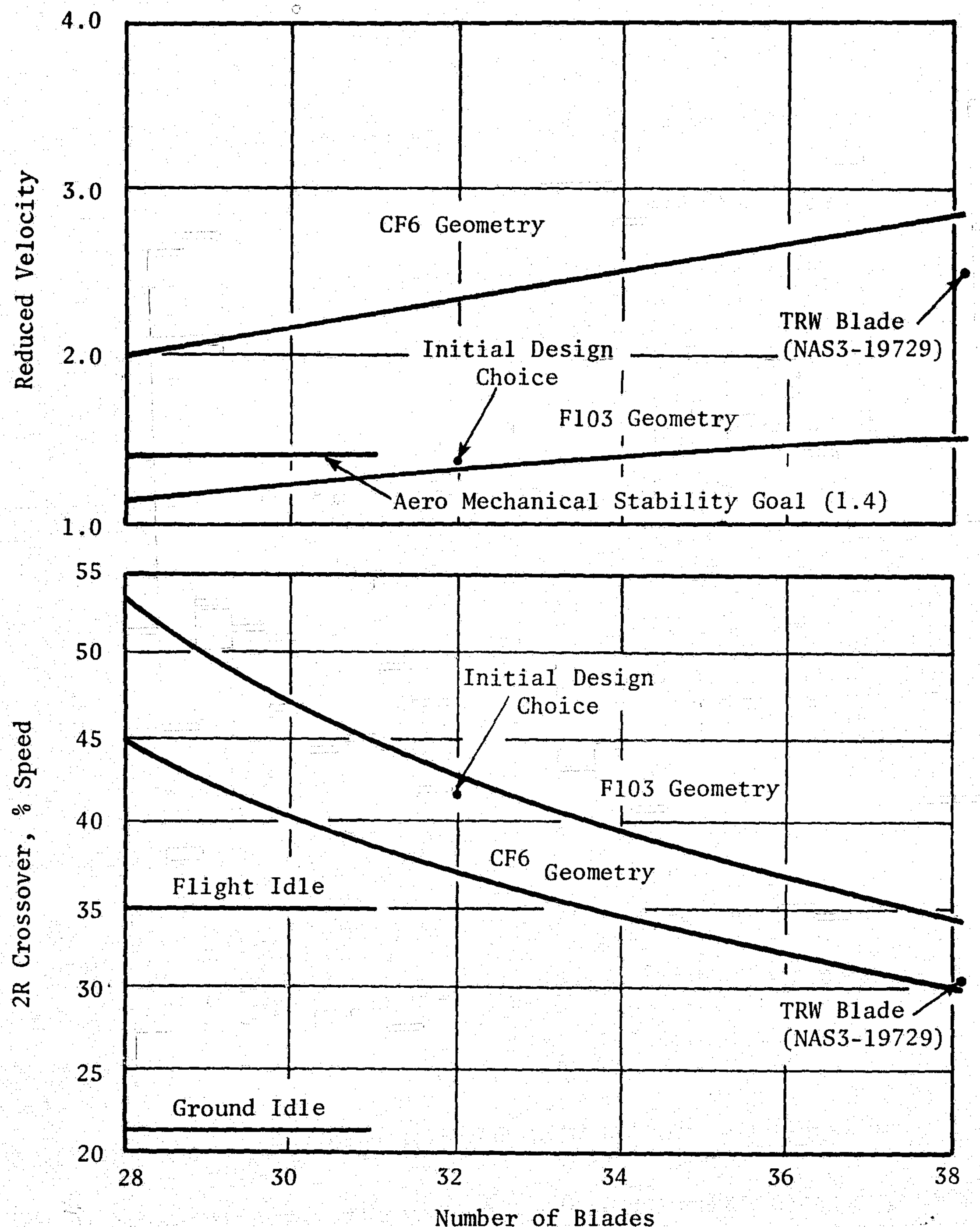

Figure 6. Reduced Velocity and 2/Rev Cross-Over Parametric Study.

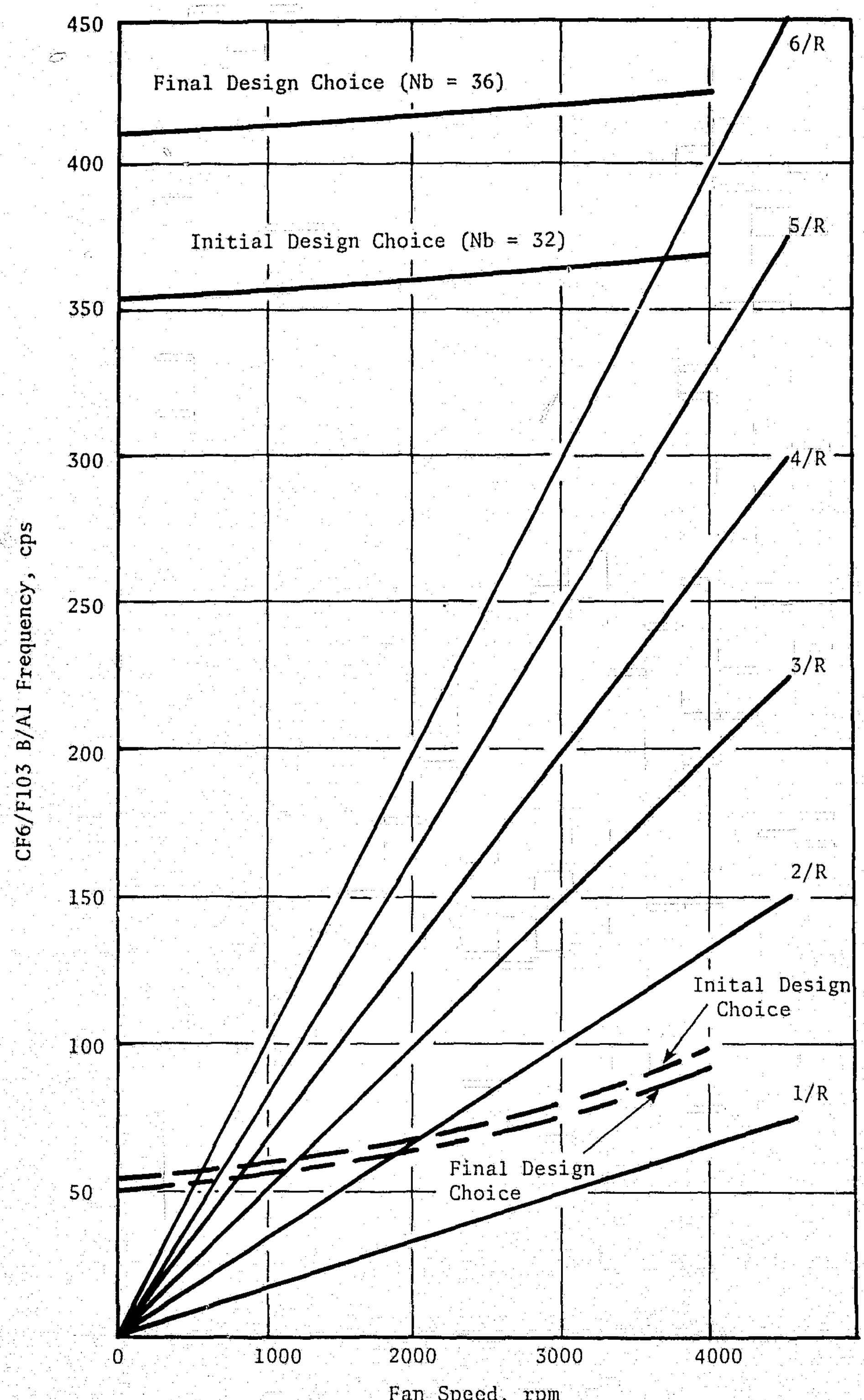

Figure 7. B/Al Fan Blade Frequency Parametric Study.

aeromechanical stability limit of 1.36. First flex ranges from 50.6 cps to 94.6 cps, zero rpm, and 3950 rpm, respectively, while first torsion ranges from 410.1 to 423.8 cps.

3.2.5 Steady State Stress

For preliminary blade design considerations, average radial stresses are all that are generated, plus taking into consideration dovetail size and its ability to hold the blade. Blade dovetail and disk post stresses are evaluated both for normal design conditions and blade-out conditions. The maximum average radial stress in the blade root region for the preliminary designs is 31 to 32 ksi, maximum average disk post radial stress in the post-neck is 26 ksi and the blade dovetail tang shear stress is 6 to 9 ksi. Blade out disk post stresses are as high as 86 to 100 ksi. For fan speeds up to 3950 rpm (F103 and CF6 blade out conditions produce stresses as high as 122 and 139 ksi, respectively for fan speeds up to 4130 rpm).

3.2.6 FOD Resistance Considerations

For FOD resistant composite fan blades, leading edges must be thicker than for those for similar titanium designs. Likewise, more root thickness is required to carry the bending-type loading of an impact, Figure 8.

Leading edge thickness/chord at the 75% span location is 75% thicker than the original F103 design at the same location. Recent studies of the F103 design has indicated that this additional thickness is required in order to successfully ingest starlings at 75% span for polymeric blade designs. Leading edge thickenesses all along the blade span are thicker to insure starling impact success at any span location.

3.3 PRELIMINARY AERODYNAMIC DESIGN

In late 1976, an improved fan design was tested by GE for the CF6. This design was very successful where efficiency improvements of 3 to 4 points were demonstrated in the important cruise region (1350-1450 pounds per second fan flow). It is this excellent efficiency base as shown in Figure 9 on which the boron-aluminum blade design will be rated.

The primary benefit aerodynamically of the B/Al blade is elimination of the part span shroud, particularly in the started flow region above 1450 pounds per second. In this region, an efficiency improvement of 1.2 points is expected based on traverse data from the improved fan test. At lower flows around 1350 pounds per second, the shroud wake (local pressure hole) diminishes significantly. Hence, on an apparent basis, the shroud loss effect diminishes and efficiency improvements may not be realized at these flows. This is not conclusive, however, because other tests have shown significant spanwise effects due to the part span shroud. Testing will be required to determine the part span loss effect during unstarted flow conditions.

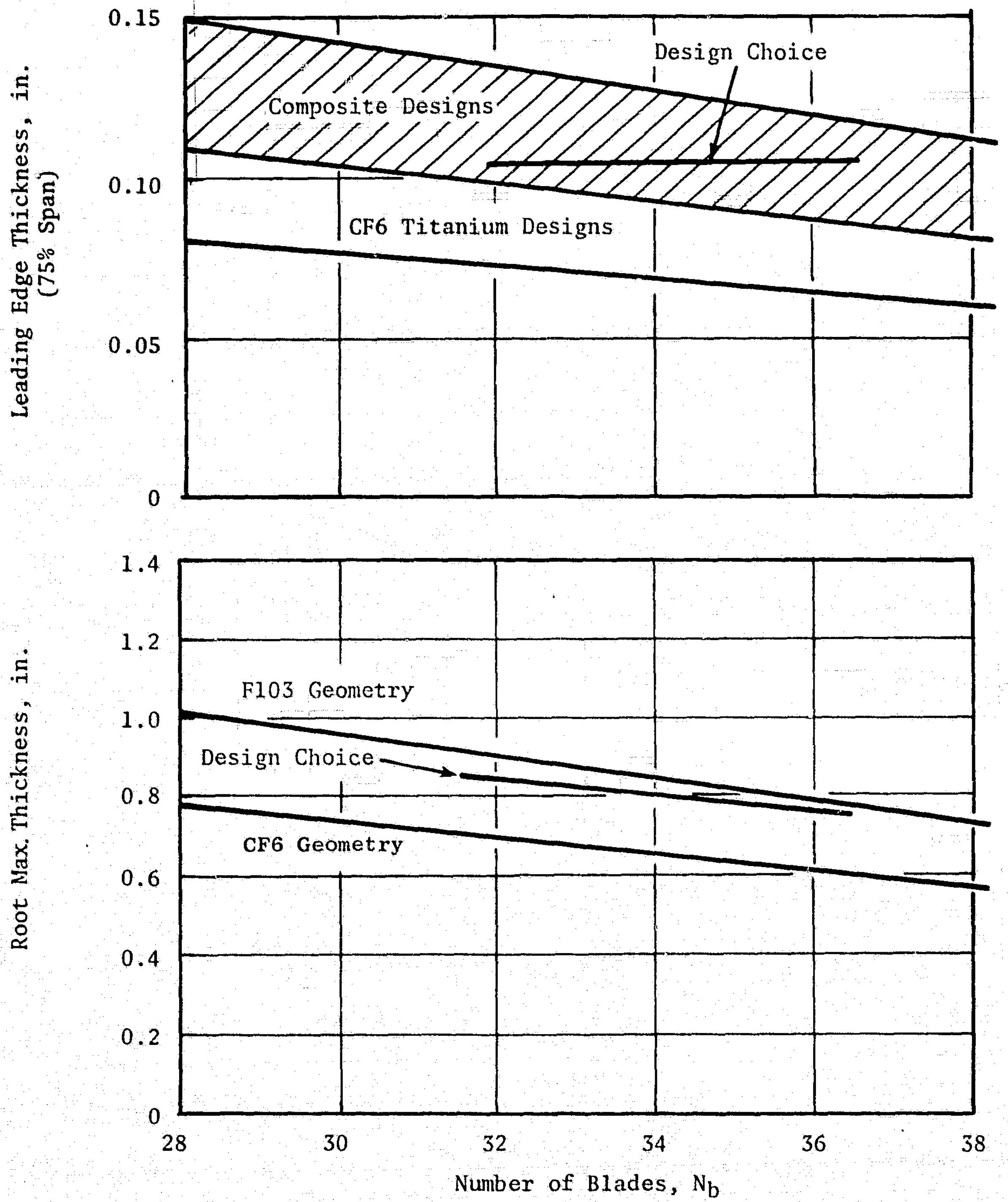

Figure 8. Leading Edge and Root Thickness Parametric Study.

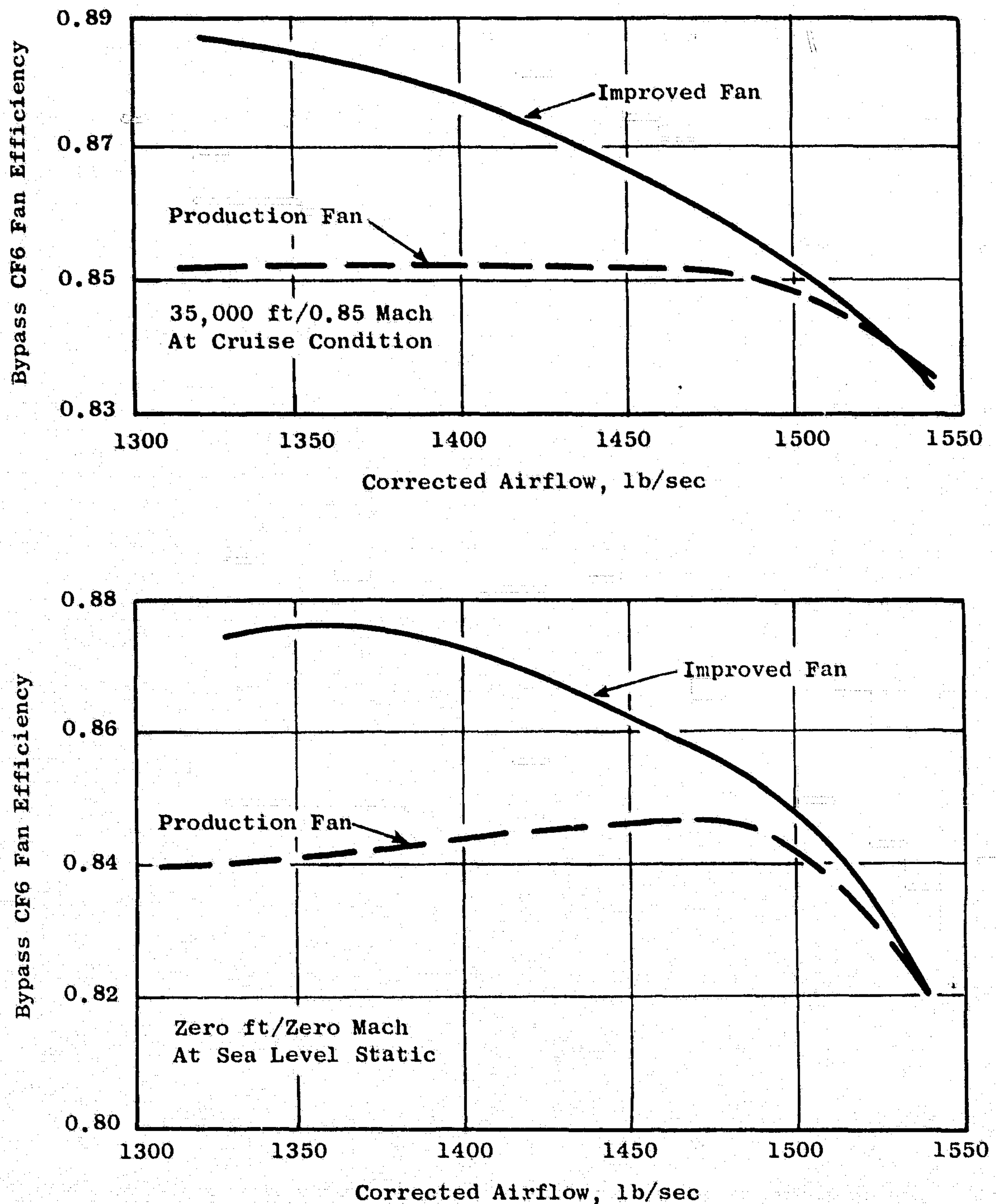

Figure 9. CF6 Fan Efficiencies.

Along with the efficiency gain, there is a loss factor due to increased section thicknesses required for aeromechanic and ruggedization requirements. The increased leading edge and maximum thicknesses obviously result in greater leading-edge wedge angles and bow shock losses. More critical is the reduction in passage area, and a resultant loss in flow pumping capability with increased passage entrance shock losses. The flow pumping can hopefully be regained by increasing the area through opening of the blade. Suction surface Mach numbers, however, cannot be reduced and increased losses will be experienced.

The thickness distributions for the 32 and 36 blade design at constant solidity are shown in Figure 10. These thickness increases are similar to internal aero design analysis which have been made for the CF6-50 fan blade. Performance loss estimates are made for the B/Al blade relative to the internal GE studies since the contractual commitments of the B/Al program aerodynamically require that the aero design is reasonable, sufficient for aero mechanical testing, and not performance qualified.

Blade-to-blade aerodynamic solutions for a thickened blade relative to the current improved fan blade are shown in Figures 11 and 12. For the thickened case, the meanline has been arbitrarily reshaped to control specific area requirements between inlet, mouth, throat, and exit. Incidence and deviation angles were also maintained within current experience. As can be observed in the upper right hand corner of these figures, the bow shock initially reduces the suction surface Mach number, but it is then expanded to a higher Mach number in the mouth and throat regions. Analysis of the Mach number distributions resulting in shock loss estimates for the started conditions plus the bow shock loss yields the efficiency loss due to the increased leading edge and maximum thicknesses. These are summarized in Tables III and IV.

Also shown on Tables III and IV are performance losses due to aspect ratio or secondary flow at the end wall regions. The secondary flow is induced by the static pressure gradients in the passage and its build-up is increased as the passage length increases.

3.4 PRELIMINARY BLADE DRAWINGS

Working layout-type drawings were generated for the preliminary blade design effort. Three drawings define the molded 36 blade design:

1. Large B/Al fan blade preliminary design 4013057-923.

2. Shank sections large B/Al blade preliminary design 4013057-927.

3. Five sheets of cross-sections consisting of 22 blade sections (no number assigned).

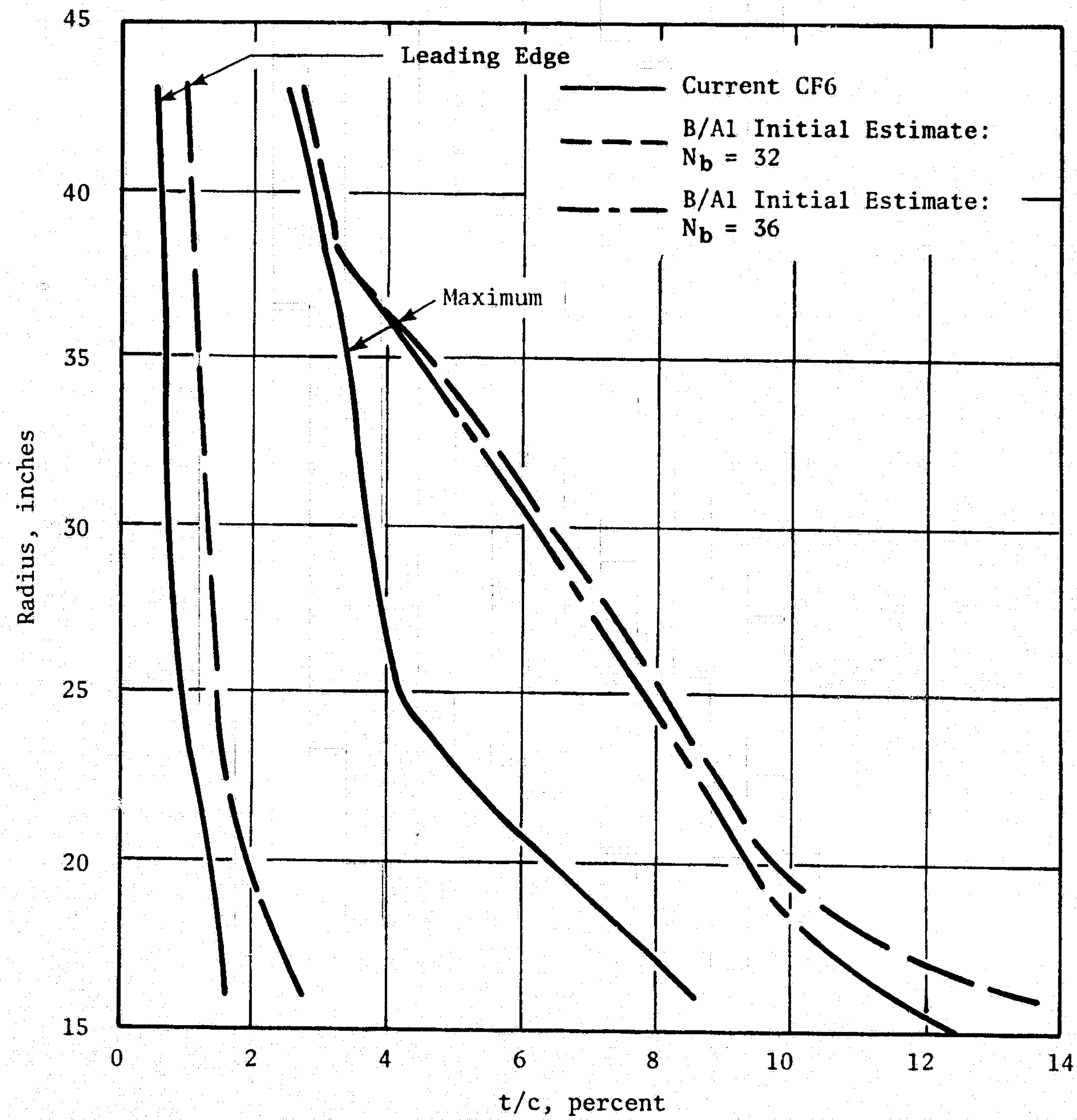

Figure 10. Thickness Distribution Comparisons.

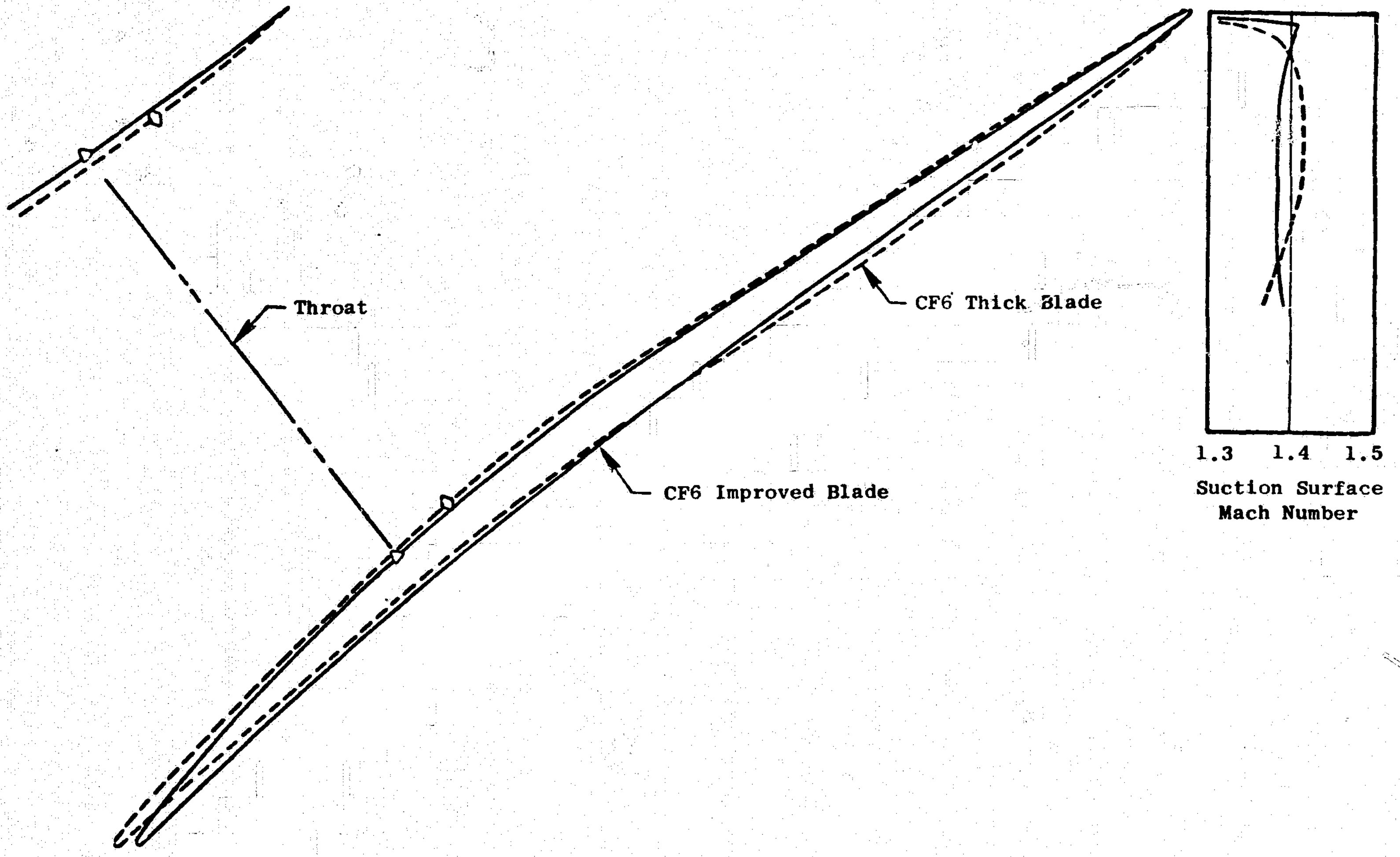

Figure 11. Comparison of a Thick and a Thin Airfoil Section, $M_{IR} = 1.324$, R = 37.0 Inches.

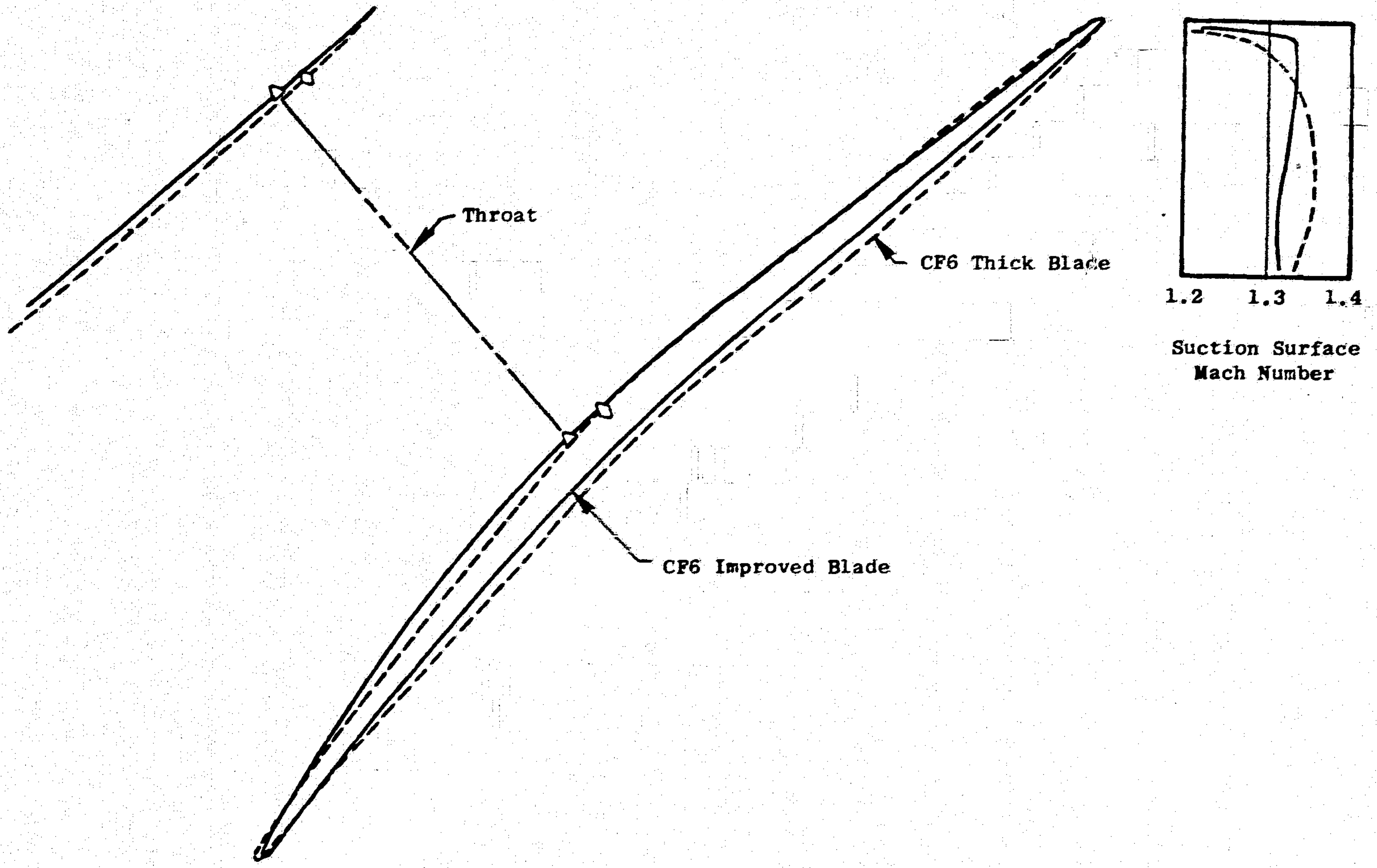

Figure 12. Comparison of a Thick and a Thin Airfoil Section, $M_{IR} = 1.234$, R = 32.5 Inches.

Table III. Estimated Fan Efficiency Deltas for a Boron/Aluminum Blade.

(N_B = 38 to 32 at Constant Solidity)

(High Flow Range: 1450 to 1480 lb/sec)

	$\Delta\eta$ Bypass Pts.	$\Delta\eta$ Hub Pts.	$\Delta\eta$ Booster Pts.
Lower AR/Secondary Flow	-0.2	-0.1	-0.05
Leading Edge Thickness	-1.6	0	0
Maximum Thickness	-0.2	-0.6	-0.3
Part Span Shroud Removal	+1.2	---	---
Net	-0.8	-0.7	-0.35

Note: Effect on Cruise sfc: $\Delta sfc/\Delta\eta_{BP} = -0.5\%/\%$

$\Delta sfc/\Delta\eta_{B} = -0.25\%/\%$

Table IV. Estimated Fan Efficiency Deltas for a Boron/Aluminum Blade.

(N_B = 38 to 36 at Constant Solidity)

(High Flow Range: 1450 to 1480 lb/sec)

	$\Delta\eta$ Bypass Pts.	$\Delta\eta$ Hub Pts.	$\Delta\eta$ Booster Pts.
Lower AR/Secondary Flow	-0.07	-0.03	-0.015
Leading Edge Thickness	-1.6	0	0
Maximum Thickness	-0.2	-0.5	-0.25
Part Span Shroud Removal	+1.2	---	---
Net	-0.67	-0.53	-0.265

Note: Effect on Cruise sfc: $\Delta sfc/\Delta\eta_{BP} = -0.5\%/\%$

$\Delta sfc/\Delta\eta_{B} = -0.25\%/\%$

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TABLE 1

SECT	AIRFOIL SECTION HEIGHT	TWIST ANGLE	THICKNESS LEAD	THICKNESS MAX	THICKNESS TRAIL	CHORD OVERALL	RADIUS TRAIL EDGE REF	CAMBER ANGLE LEAD	CAMBER ANGLE TRAIL	DROP LEAD	DROP TRAIL	ENGINEERING MASTER NO.
A-A	1.865	—	.415	.720	—	—				—	—	SHT 1
B-B	2.141	—	.360	.700	—	—				—	—	1
C-C	3.728	—	.175	.685	—	—				—	—	1
D-D	5.131	—	.160	.670	—	—				—	—	1
E-E	5.858	11°53'	.150	.665	.172	7.154				—	—	1
F-F	7.803	15°48'	.129	.640	.157	7.450				—	—	2
G-G	11.285	31°5'	.121	.596	.153	8.034				—	—	2
H-H	12.204	33°30'	.120	.578	.151	8.180				—	—	2
J-J	14.150	38°0'	.118	.535	.146	8.490				—	—	2
K-K	16.606	42°53'	.115	.475	.140	8.887				—	—	2
L-L	17.782	45°23'	.113	.444	.137	9.068				—	—	3
M-M	18.859	48°8'	.112	.412	.134	9.249				—	—	3
N-N	20.489	52°20'	.109	.370	.129	9.515				—	—	3
P-P	21.872	54°56'	.107	.337	.125	9.740				—	—	4
R-R	22.953	56°40'	.105	.313	.122	9.904				—	—	4
S-S	24.898	60°3'	.102	.291	.116	10.265				—	—	4
T-T	25.768	62°8'	.101	.291	.113	10.467				.055	.045	4
U-U	26.649	63°48'	.100	.291	.111	10.680				.065	.055	4
V-V	27.969	66°12'	.099	.293	.107	11.022				.090	.070	5
W-W	29.300	68°27'	.098	.294	.103	11.382				.110	.070	5
X-X	1.000	—	—	—	—	—				—	—	1
PA	0	—	—	—	—	—				—	—	1

TABLE 2

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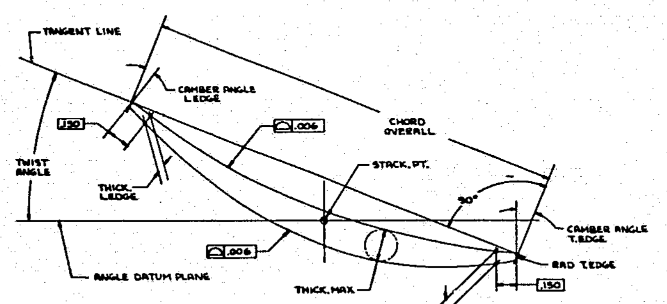
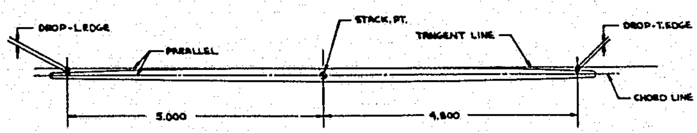
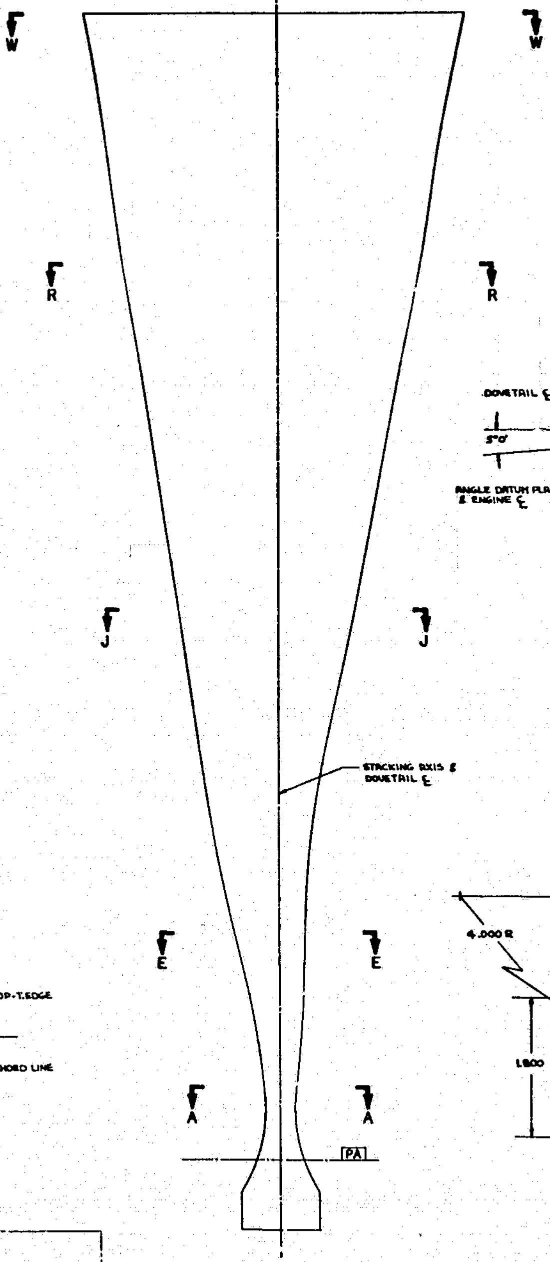
A2	1
A3	1
A4	1
A5	1

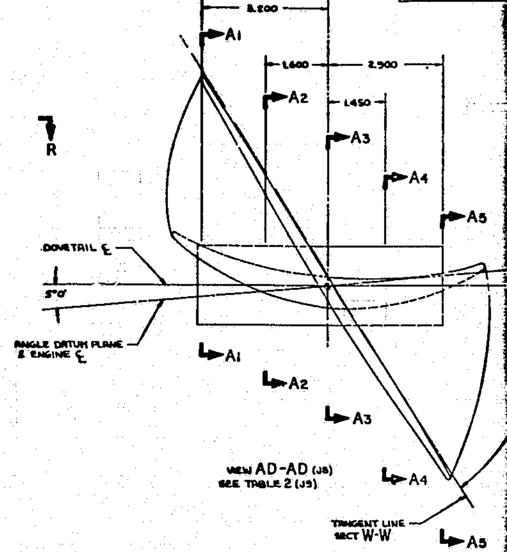


SECT E-E THRU S-S
SCALE - NONE
SEE TABLE 1 (J15)

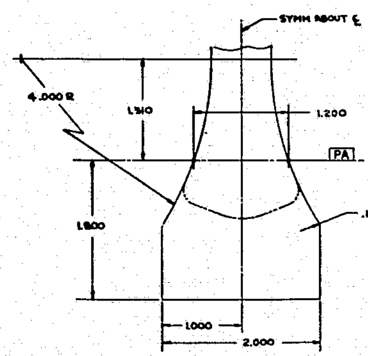


SECT T-T THRU W-W
DEFINITION OF TANGENT LINE
OTHERWISE SAME AS
SECT E-E THRU S-S
SCALE - NONE
SEE TABLE 1 (J15)





VIEW AD-AD (J8)
SEE TABLE 2 (J9)



BASIC DOVETAIL CONTOUR
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J 4013057-923

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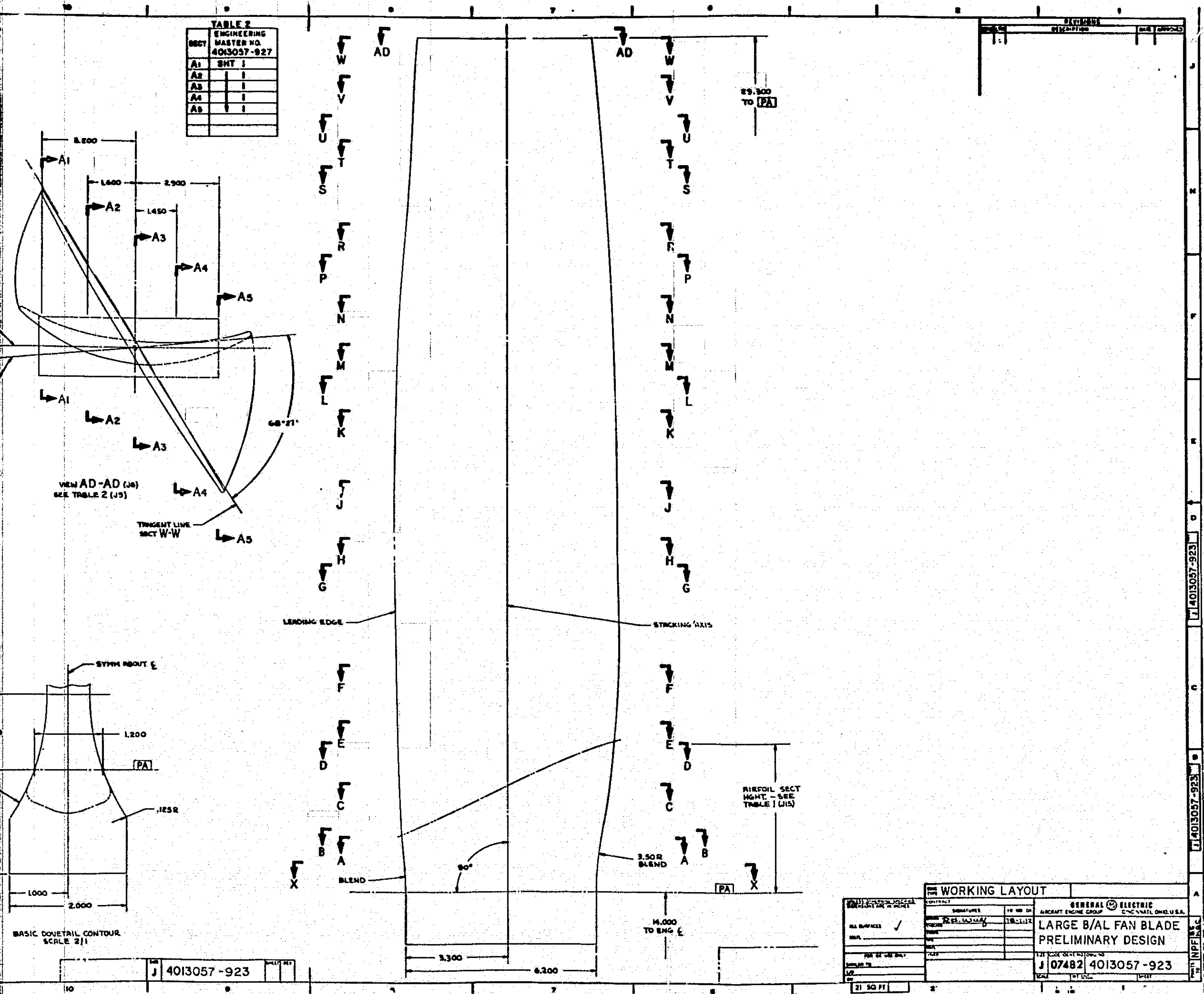

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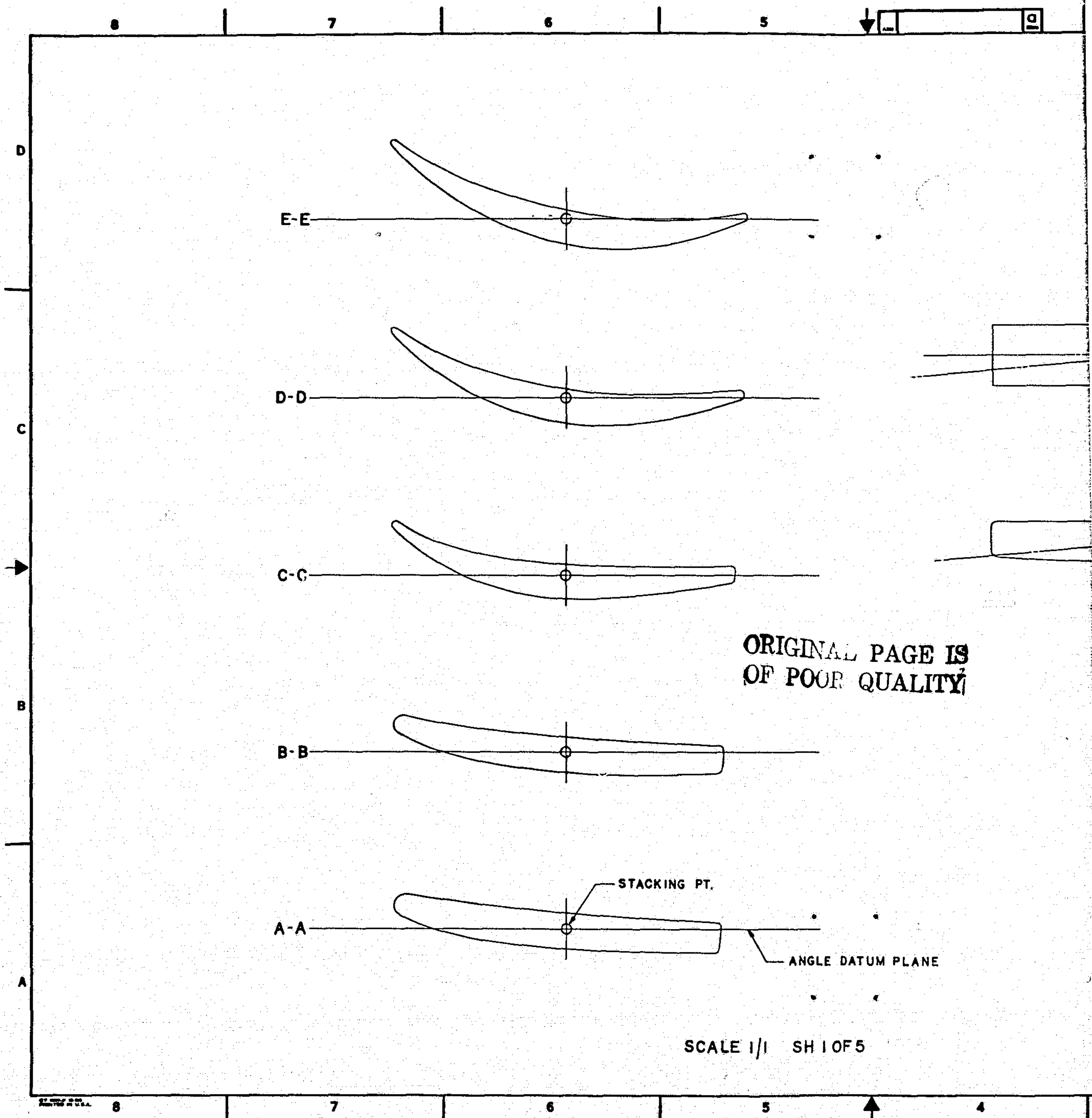

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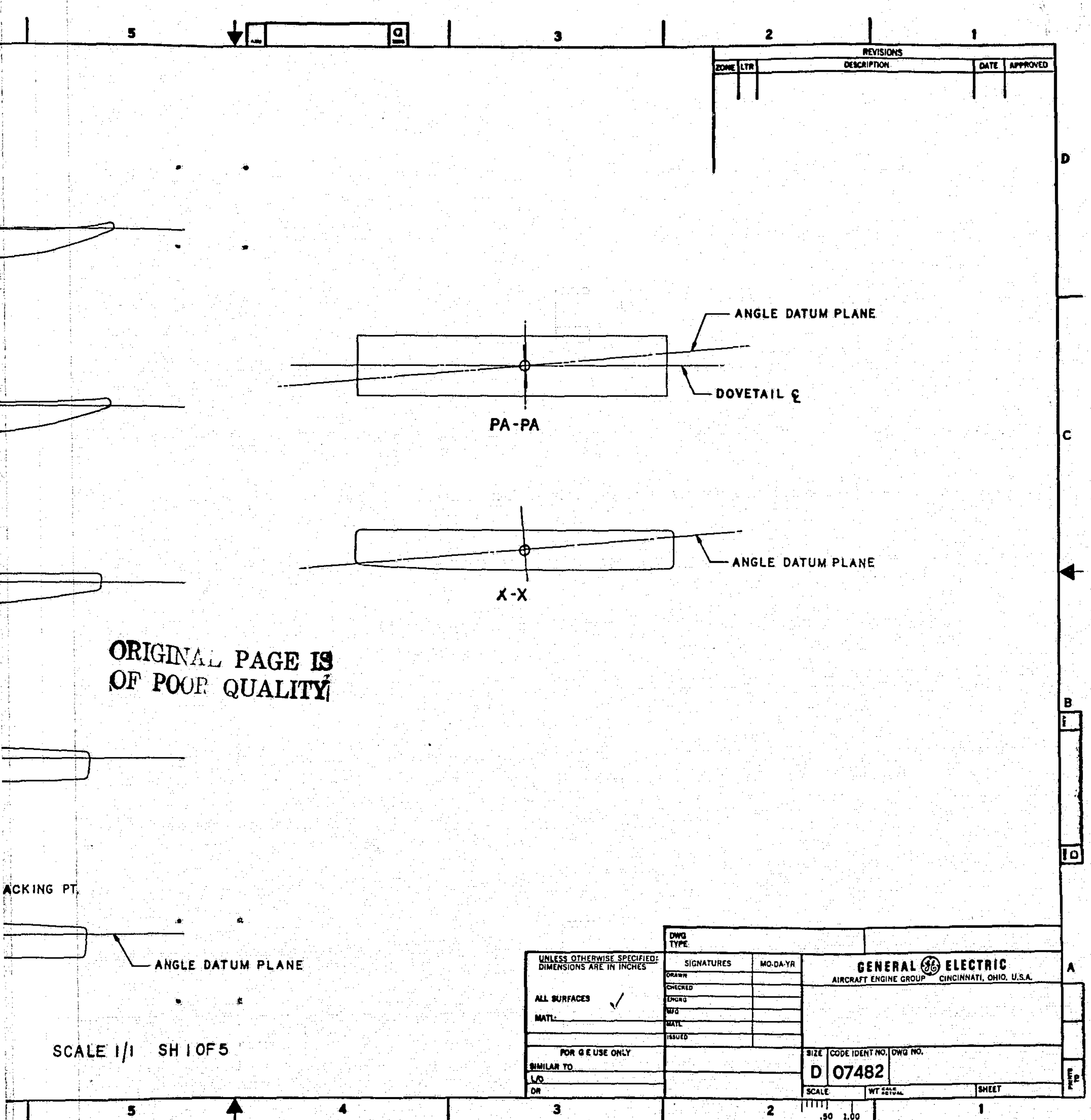

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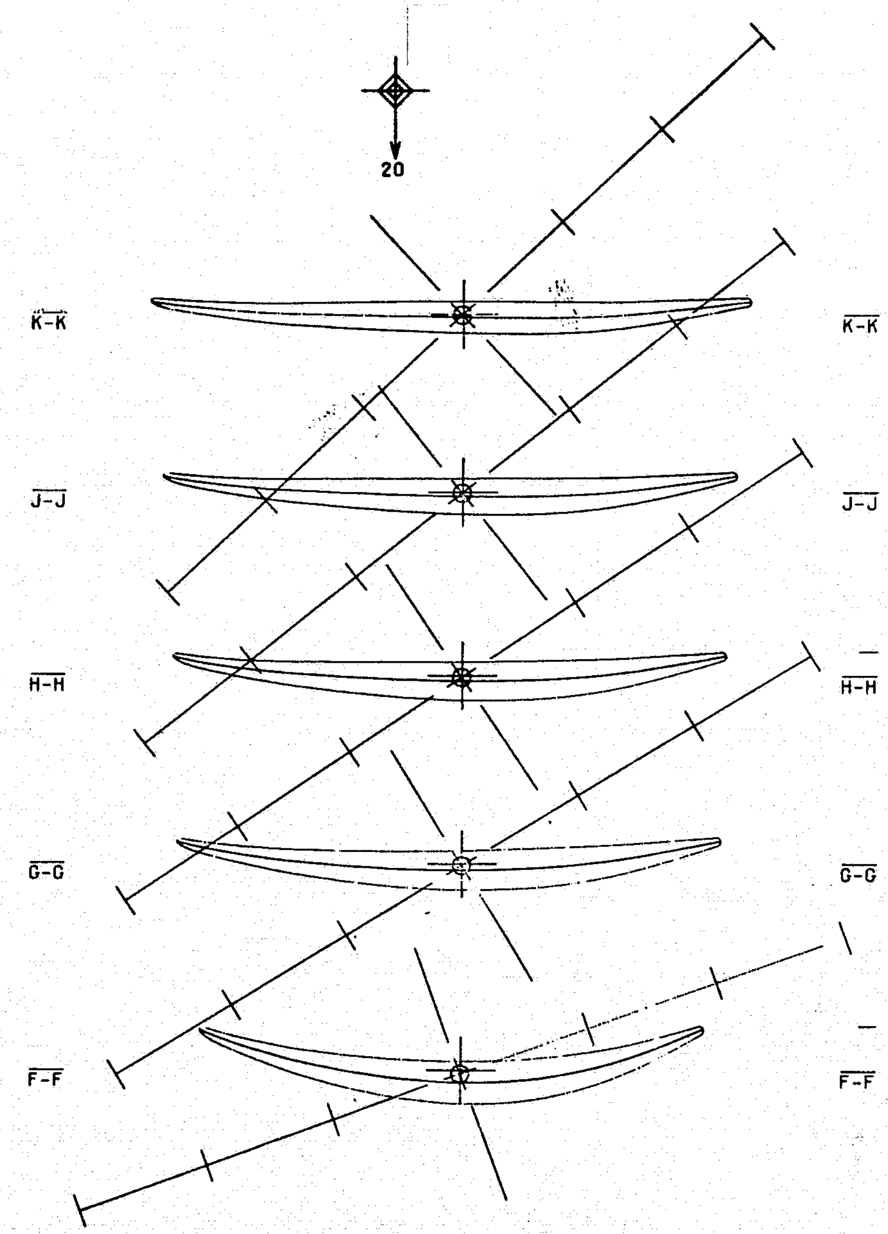

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2 INCREMENTAL SPACING OF DIVISIONS ON ANGLE DATUM IS 2.0

SCALE 1/1 SH 2 OF 5

1 PERIODICALLY CHECK TRAMMEL POINTS.PERMISSIBLE VARIATIONS .0002/IN,.005 MAX TOTAL. ALLOW FOR ATMOSPHERIC VARIATION FROM THAT STATED HEREON:
THERMAL EXPANSION 15X10⁻⁶ IN/IN/DEGREES F
HUMIDITY EXPANSION 12X10⁻⁶ IN/IN PERCENT RH

COOR REEL 00654

2 INCREMENTAL SPACI

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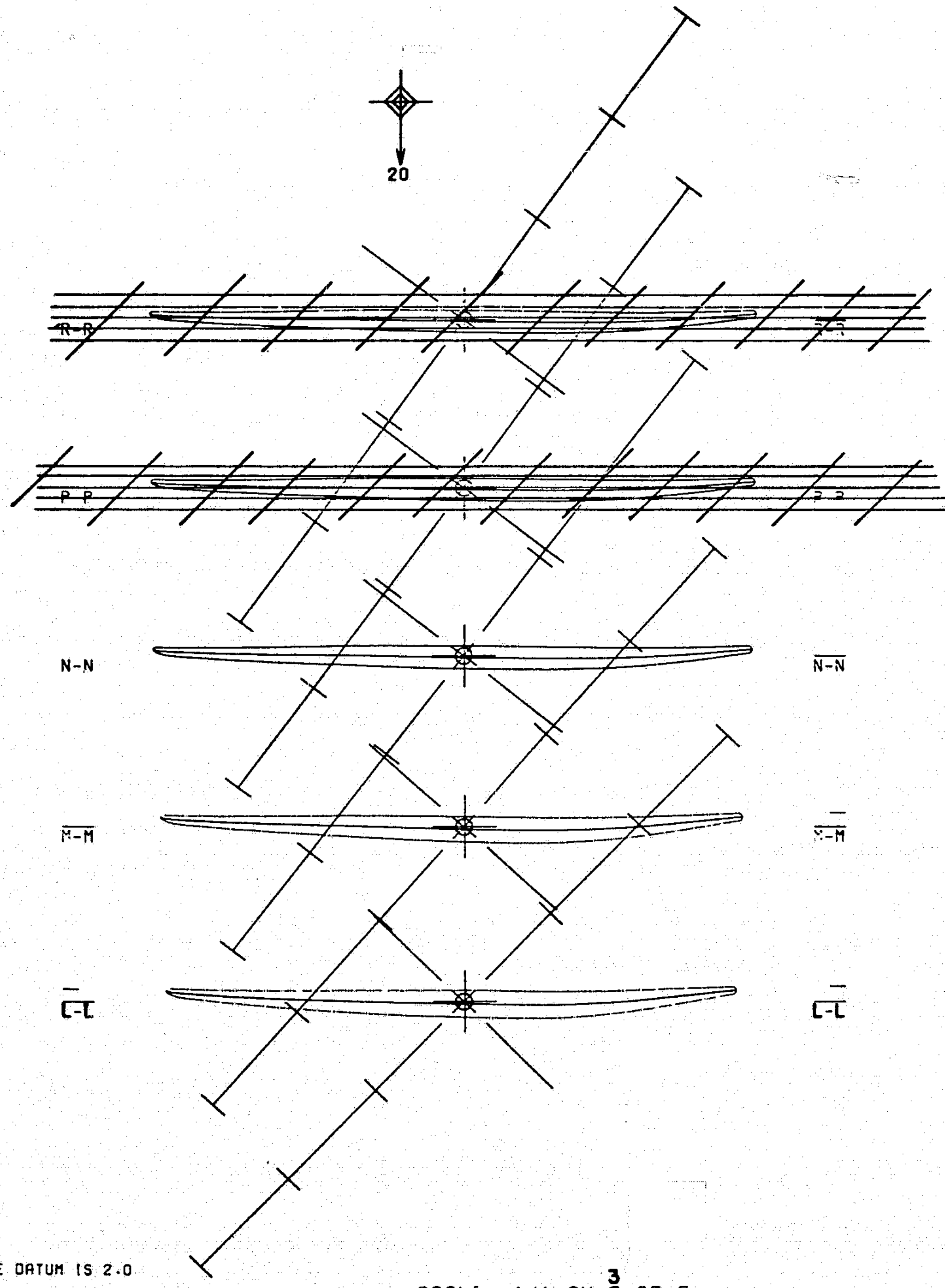

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2 INCREMENTAL SPACING OF DIVISIONS ON ANGLE DATUM IS 2.0

1 PERIODICALLY CHECK TRAMMEL POINTS.PERMISSIBLE VARIATIONS .0002/IN..005 MAX TOTAL. ALLOW FOR ATMOSPHERIC VARIATION FROM THAT STATED HEREON:
THERMAL EXPANSION 15X10⁻⁶ IN/IN/DEGREES F
HUMIDITY EXPANSION 12X10⁻⁶ IN/IN PERCENT RH

SCALE 1/1 SH 3 OF 5

COOR REEL 00654

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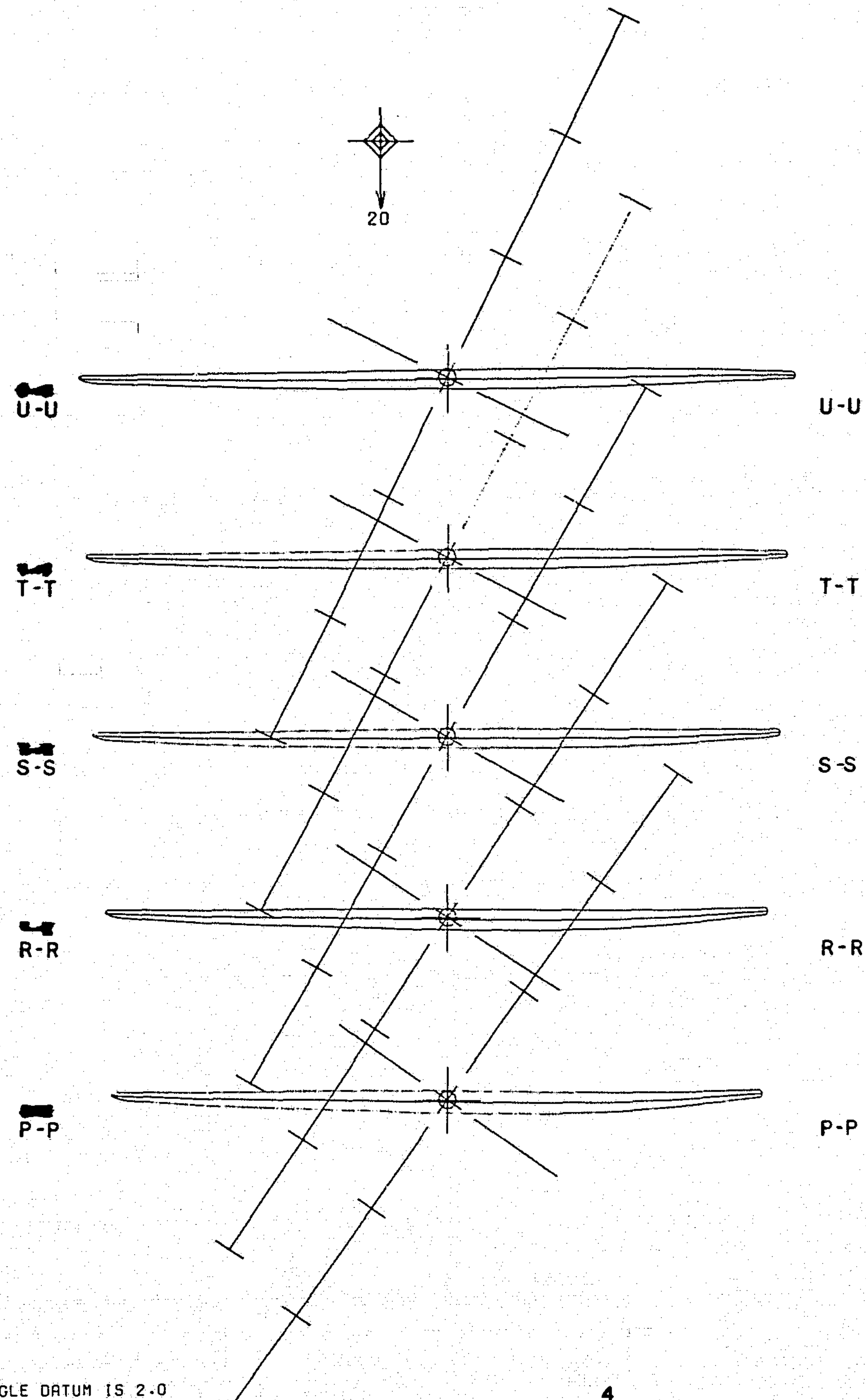

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SCALE 1/1 SH 4 OF 5

2 INCREMENTAL SPACING OF DIVISIONS ON ANGLE DATUM IS 2.0

1 PERIODICALLY CHECK TRAMMEL POINTS.PERMISSIBLE VARIATIONS .0002/IN..005 MAX TOTAL. ALLOW FOR ATMOSPHERIC VARIATION FROM THAT STATED HEREON:
THERMAL EXPANSION 15X10⁻⁶ IN/IN/DEGREES F
HUMIDITY EXPANSION 12X10⁻⁶ IN/IN PERCENT RH

COOR REEL 00654

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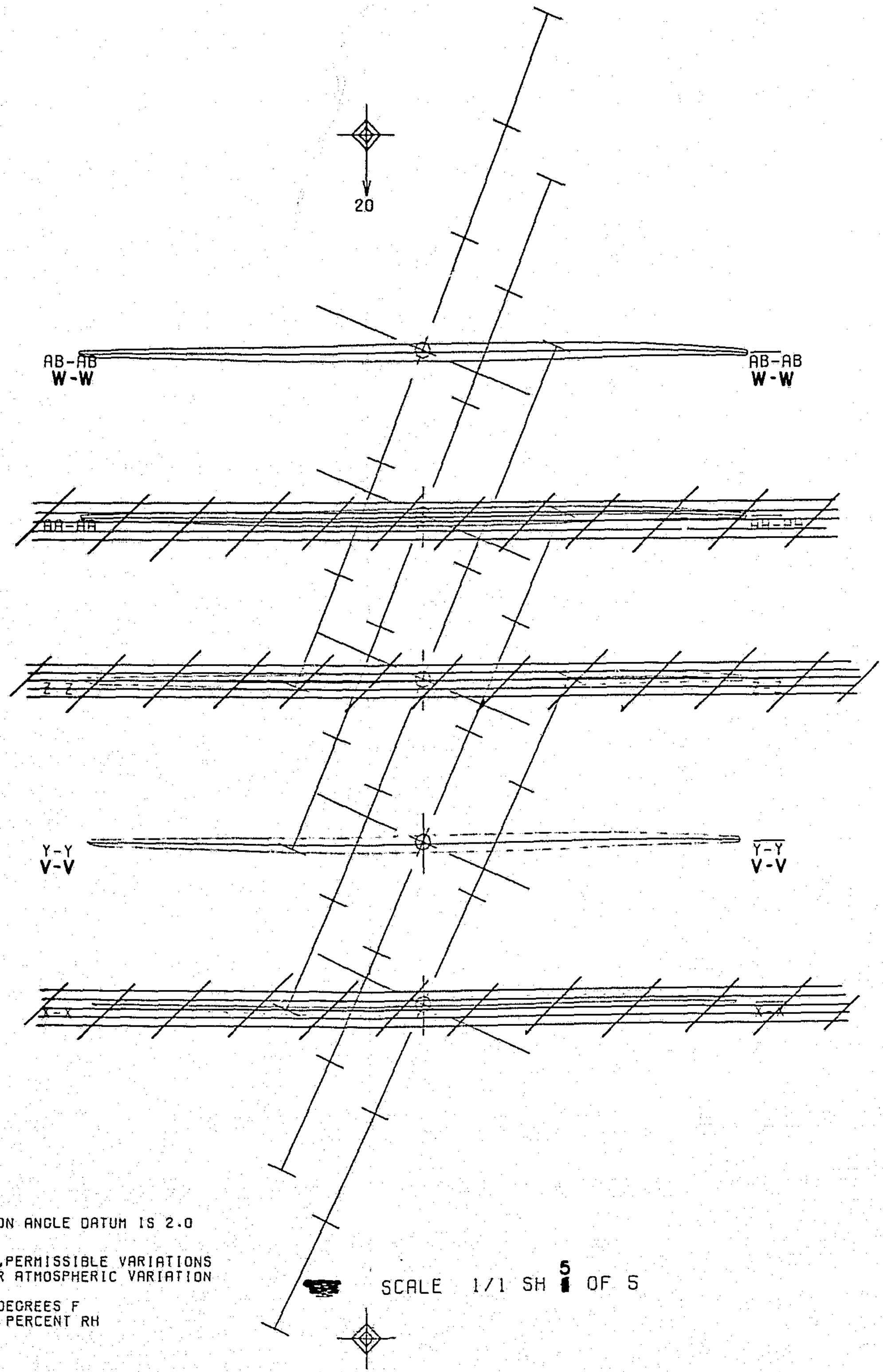

2 INCREMENTAL SPACING OF DIVISIONS ON ANGLE DATUM IS 2.0

1 PERIODICALLY CHECK TRAMMEL POINTS, PERMISSIBLE VARIATIONS
.0002/IN, .005 MAX TOTAL. ALLOW FOR ATMOSPHERIC VARIATION
FROM THAT STATED HEREON:
THERMAL EXPANSION $15X10^{-6}$ IN/IN/DEGREES F
HUMIDITY EXPANSION $12X10^{-6}$ IN/IN PERCENT RH

SCALE 1/1 SH 5 OF 5

COOR REEL 00654

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4.0 DETAILED MECHANICAL DESIGN

4.1 AERODYNAMIC DESIGN

Design of the boron aluminum blade is based on the CF6 improved blade design where the chord was increased to maintain the same solidities as shown in Figure 13. The design distributions of energy addition both chordal and spanwise at flow also remained the same. Several passes were made for each blade design (32 and 36 blades) to obtain reasonable throat margins and incidence angles as shown in Figures 14 and 15 for the 36-blade design. Throat margins in the mid-span region are larger than desired relative to design practice. Further aero design effort is required to optimize the throat and area distributions. The airfoil coordinates are considered adequate, however, for aero mechanic analysis. Additional aero design refinement will be done pending redesign requirements based on aeromechanical analysis.

The detailed layout procedure employed in the design of the fan blade geometry generally parallels established design procedure. In the tip region of the blade where the inlet relative flow is supersonic, the uncovered portion of the suction surface was set to ensure that the maximum flow passing capacity engine consistent with the design flow requirement. The incidence angles in the tip region were selected according to transonic blade design practice which has yielded good overall performance for previous designs. In the hub region, where the inlet flow is subsonic, incidence angles were selected from NASA cascade data correlations with adjustments from past design experience.

The blade trailing edge angle was established by the deviation angle which was obtained from Carter's rule applied to the camber of an equivalent two-dimensional cascade with an additive empirical adjustment, X. This adjustment is derived from aerodynamic design and performance synthesis for this general type of rotor.

Over the entire blade span, the minimum passage area, or throat, must be sufficient to pass the design flow including allowances for boundary layer losses, and flow nonuniformities. In the transonic and supersonic region, the smallest throat area, consistent with permitting the design flow to pass, is desirable since this minimizes over expansions on the suction surface. A further consideration was to minimize disturbances to the flow along the forward portion of the suction surface to minimize forward propagating waves that might provide an additional noise source. Design experience guided the degree to which each of these desires was applied to individual section layouts.

The resulting blade shapes have very little camber in the tip region and have arbitrary meanline shapes to obtain the desired throat margin and acceptable Mach number distributions. As the camber increases in the inner region of the blade, the meanline remains arbitrary with the majority of the camber

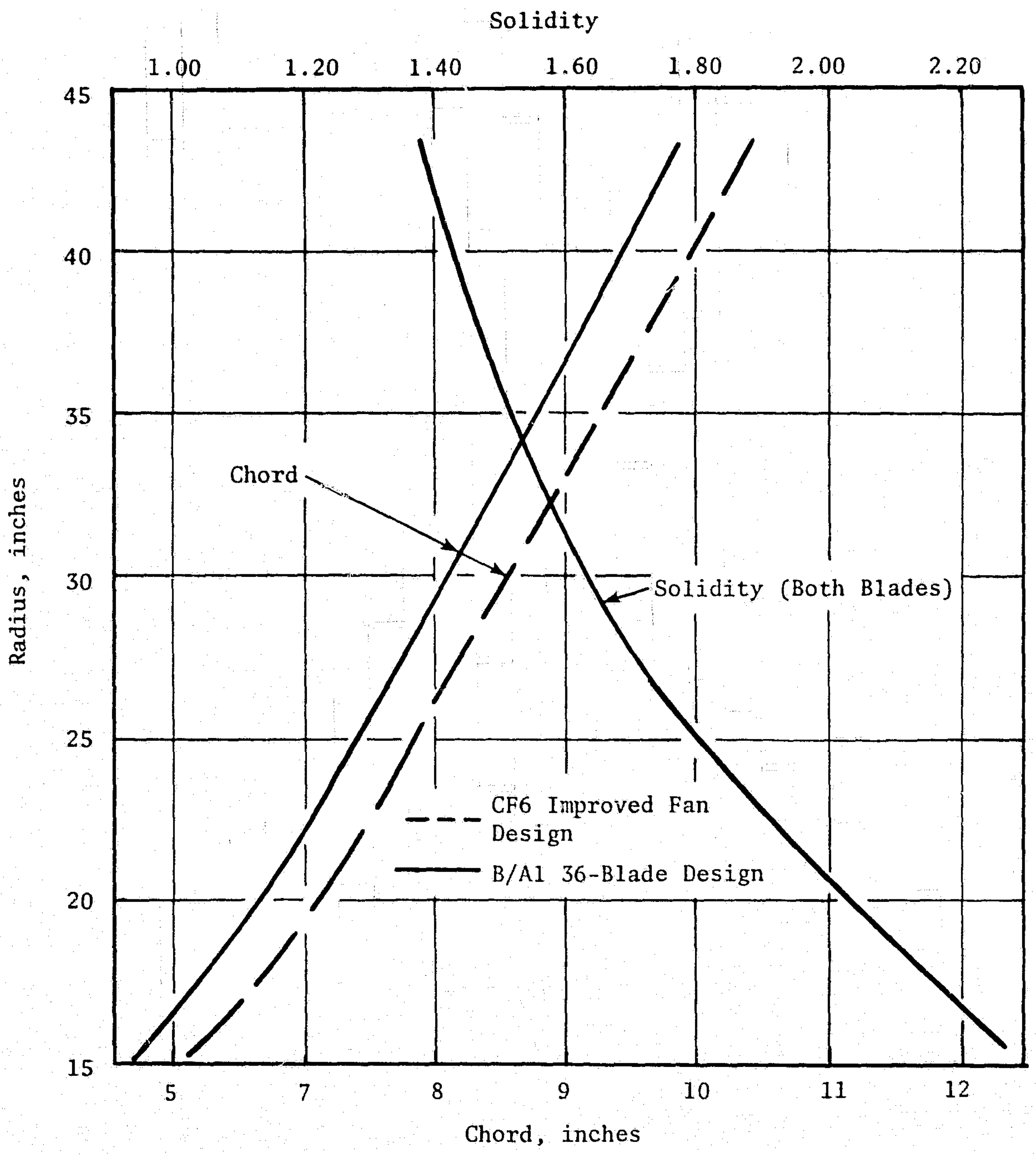

Figure 13. Chord and Solidity Comparison.

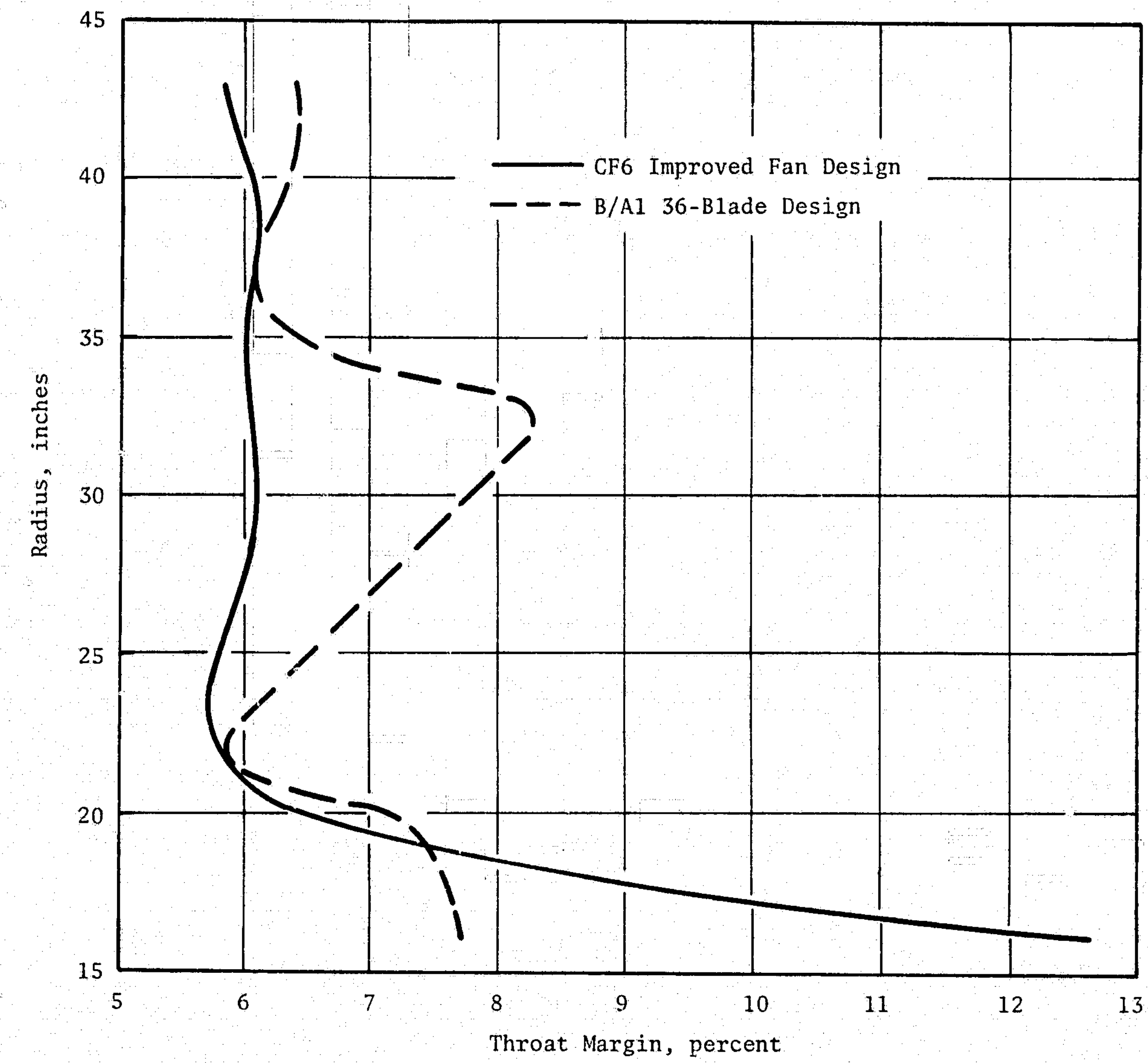

Figure 14. Throat Margin Comparison.

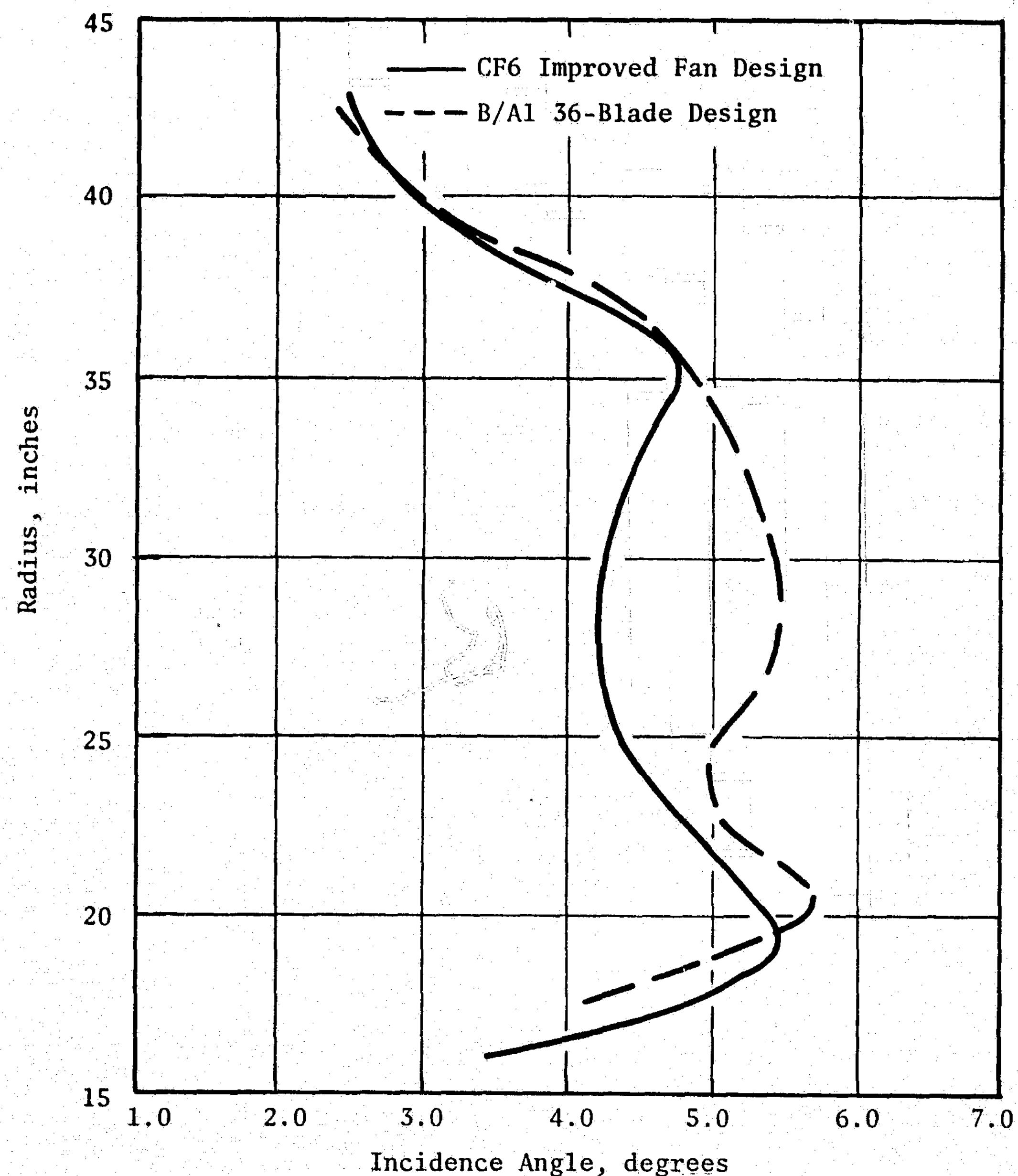

Figure 15. Incidence Angle Comparison.

in the aft portion. At the hub, the section shape is similar to double circular arc. Resulting camber and stagger radial distributions are shown in Figure 16.

Additional aero design analysis is required to render the design a performance optimized blade. The design is adequate, however, for aeromechanical evaluation. The design is also considered capable of running with adequate stability margin.

4.2 MECHANICAL DESIGN

4.2.1 Finite Element Model

The finite element model used to carry out the detailed analysis incorporated 250 elements and 473 nodal coordinates. The element distribution was one element through the thickness near the inner flowpath and three elements through the thickness in the root transition and dovetail region. Figure 17 shows the model projected into Y-Z coordinate plans. The analysis was conducted in a centrifugally stiffened field representing the 100% design speed of 4080 rpm, but did not include air loads as this type of loading is generally negligible when superimposed on blade stresses.

4.2.2 Material Properties

Material properties for this finite element analysis represent 55% fiber volume fraction, 8-mil diameter boron/aluminum material at a ply orientation of ±15° are:

Through-thickness tensile modulus	18.0×10^6 psi
Chordal tensile modulus	19.0×10^6 psi
Radial tensile modulus	35.0×10^6 psi
Chordal shear modulus	4.0×10^6 psi
Cross-fiber shear modulus	9.5×10^6 psi
Radial shear modulus	8.0×10^6 psi
Chordal plane Poisson's ratio	0.3
Cross-fiber plane Poisson's ratio	0.35
Radial plane Poisson's ratio	0.27
Density	0.095 lb/in.^{3}

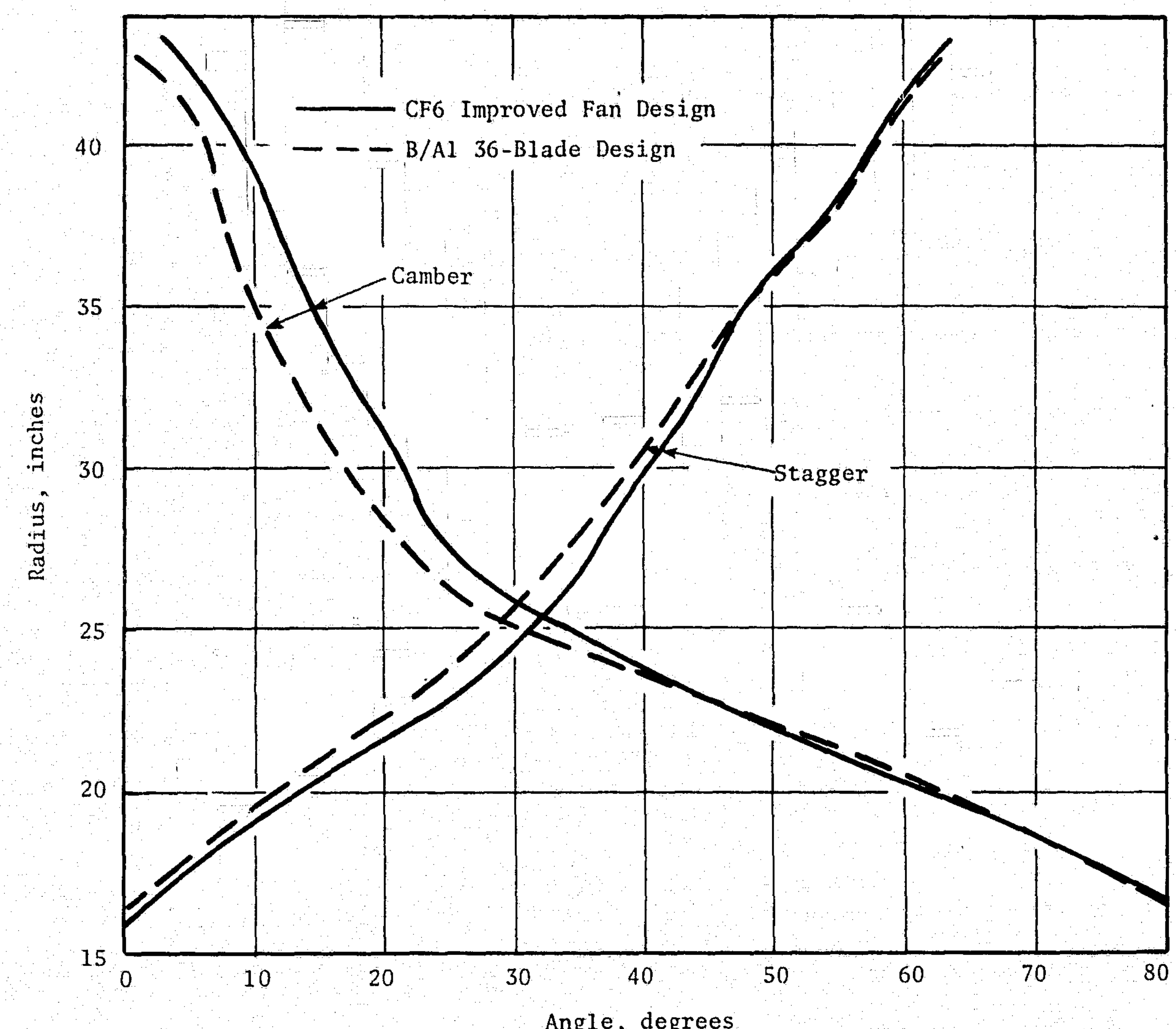

Figure 16. Camber and Stagger Comparison.

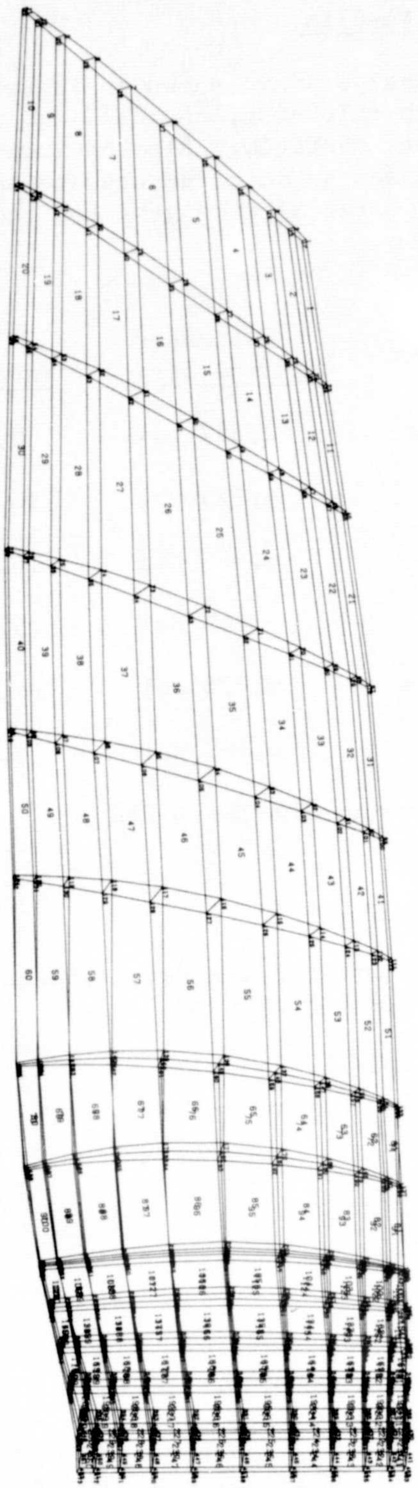

Figure 17. Finite Element Model.

4.2.3 Stress Analysis Results

Results of the stress analysis are shown in Figures 18 through 29. These figures represent the through-thickness, chordal, and radial tensile stresses on both the concave and convex surfaces. Also included are chordal, cross-fiber, and radial shear stresses on both the concave and convex surfaces. Maximum values and estimated material strengths for the six types of stresses are:

	Estimated Maximum Stress	Estimated Material Strength*
Through-Thickness Stress	2,857 psi	3,850 psi (1100 Al)
Chordal Stress	4,125 psi	10,250 psi (1100 Al)
Radial Stress	38,380 psi	114,300 psi (1100 Al)
Chordal Shear	650 psi	5,500 psi (1100 Al)
Cross-fiber Shear	9,376 psi	39,600 psi (1100 Al)
Radial Shear	6,195 psi	14,000 psi (6061 Al)

*From technical report, AFML-TR-76-218

4.2.4 Frequency Analysis Results

The first five frequency modes of the detail blade design at 4080 rpm as calculated by the finite analyses are:

First flex	117 cps
Second flex	242 cps
First torsion	374 cps
Third flex	561 cps
Fifth mode (See Figure 30.)	815 cps

The reduced velocity calculated from the above torsion frequency is 1.54 which is higher than expected from the preliminary design of 1.36. This is approximately 10% higher than the original goal of 1.4 but is within the range of other composite blades including the F103 and QCSEE.

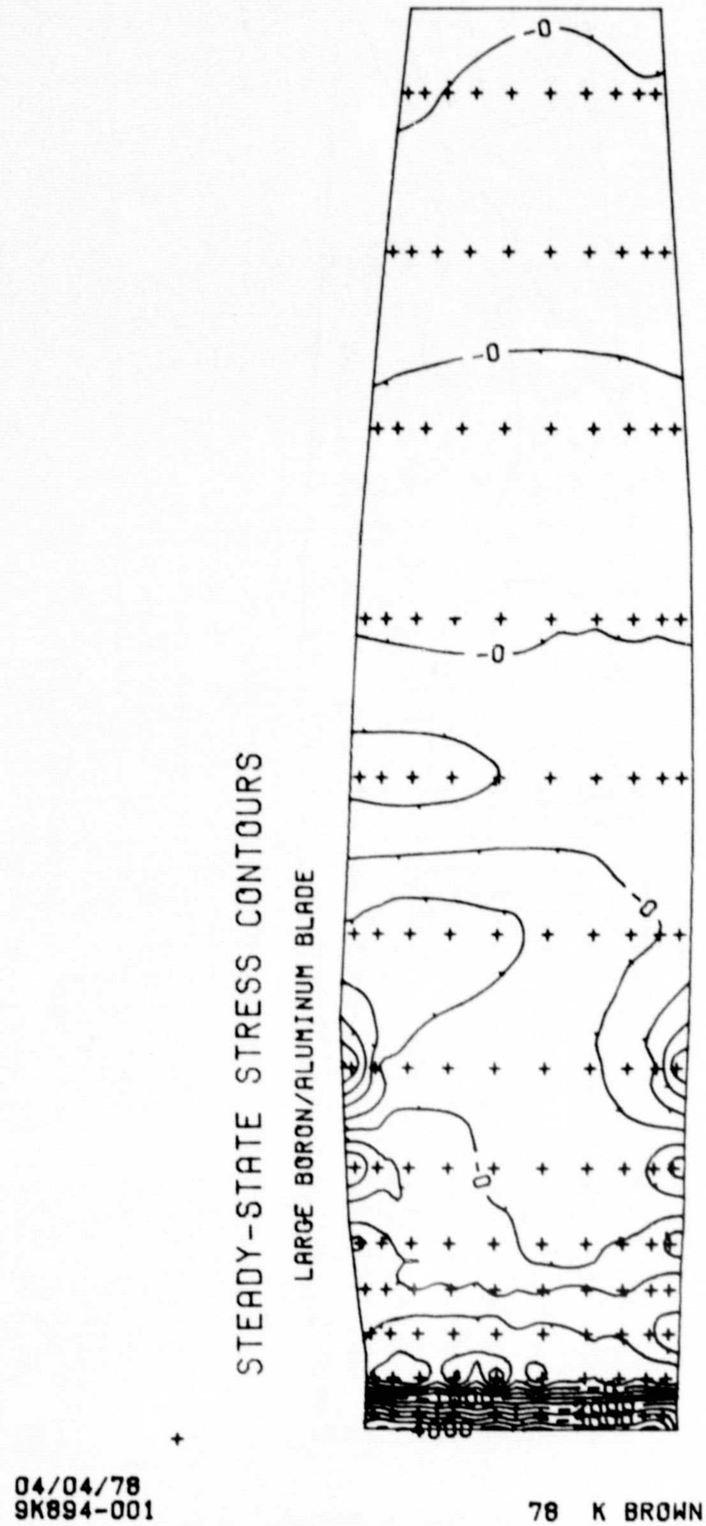

Figure 18. S11 (Thru Thickness)
Concave Surface.

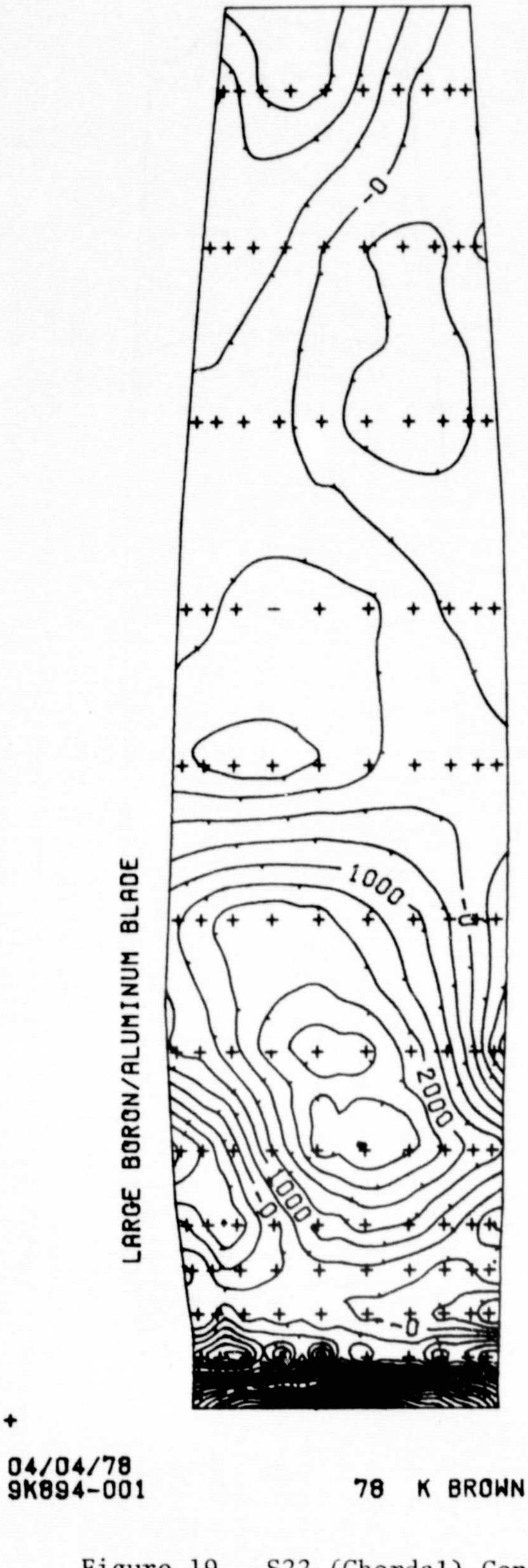

Figure 19. S22 (Chordal) Concave Surface.

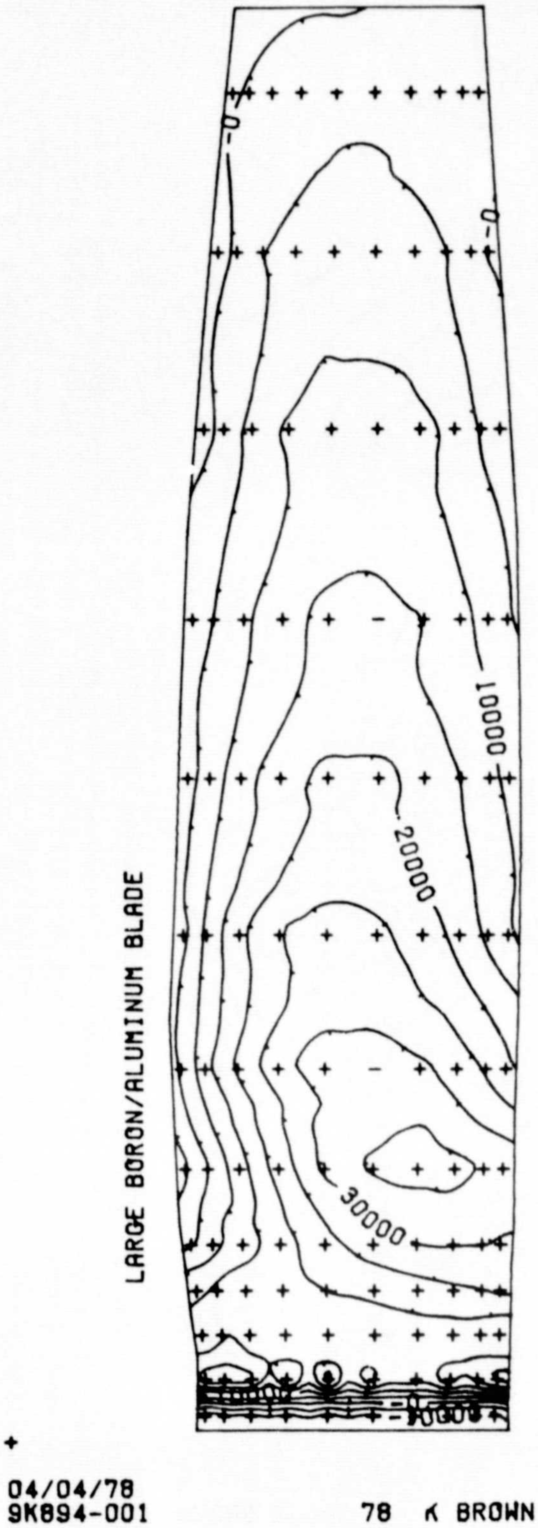

Figure 20. S33 (Radial) Concave Surface.

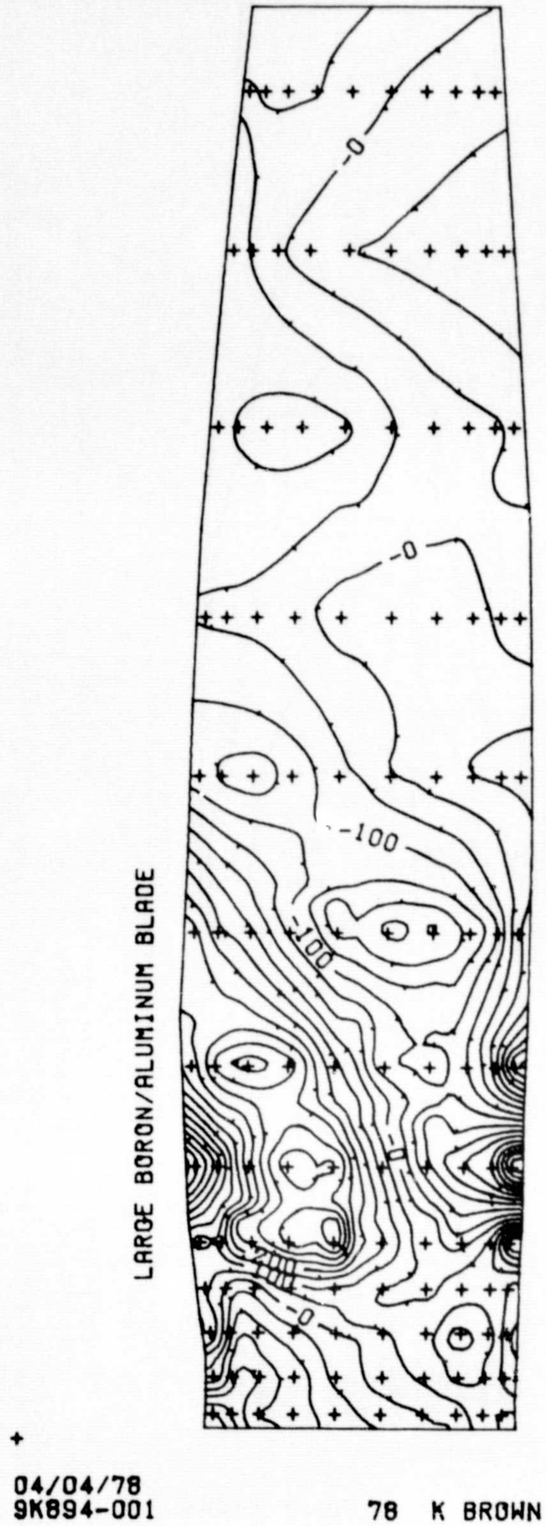

Figure 21. T12 (Chordal Shear)
Concave Surface.

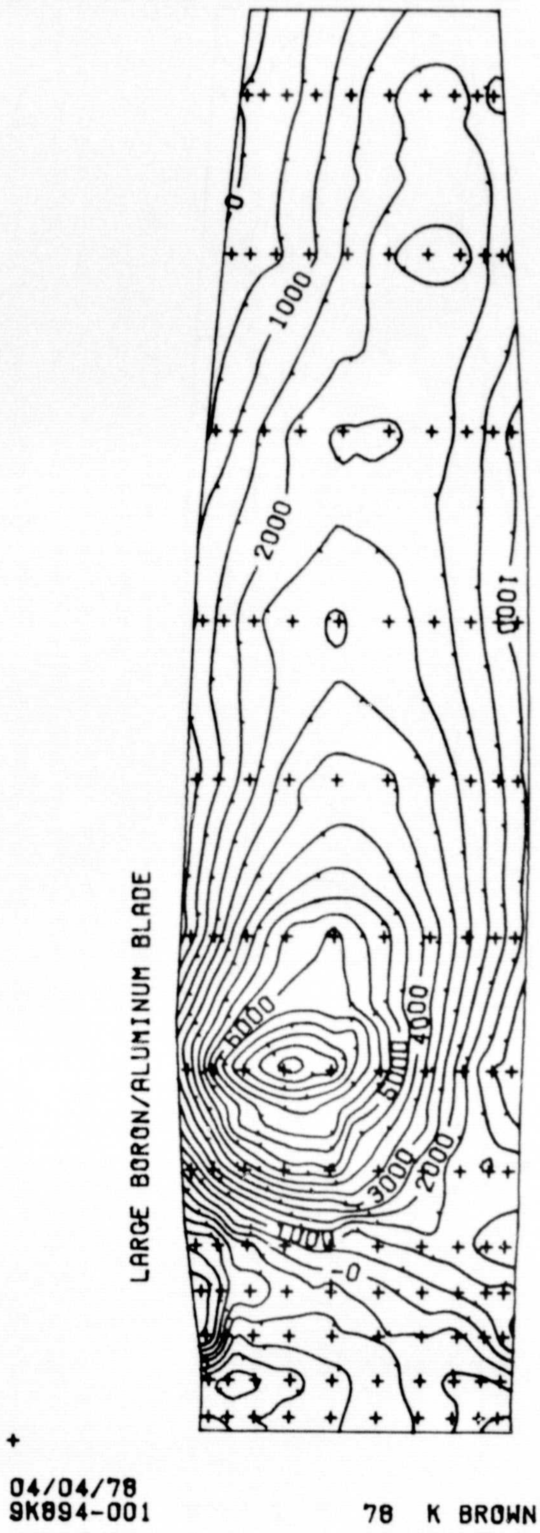

Figure 22. T23 (Cross Fiber Shear) Concave Surface.

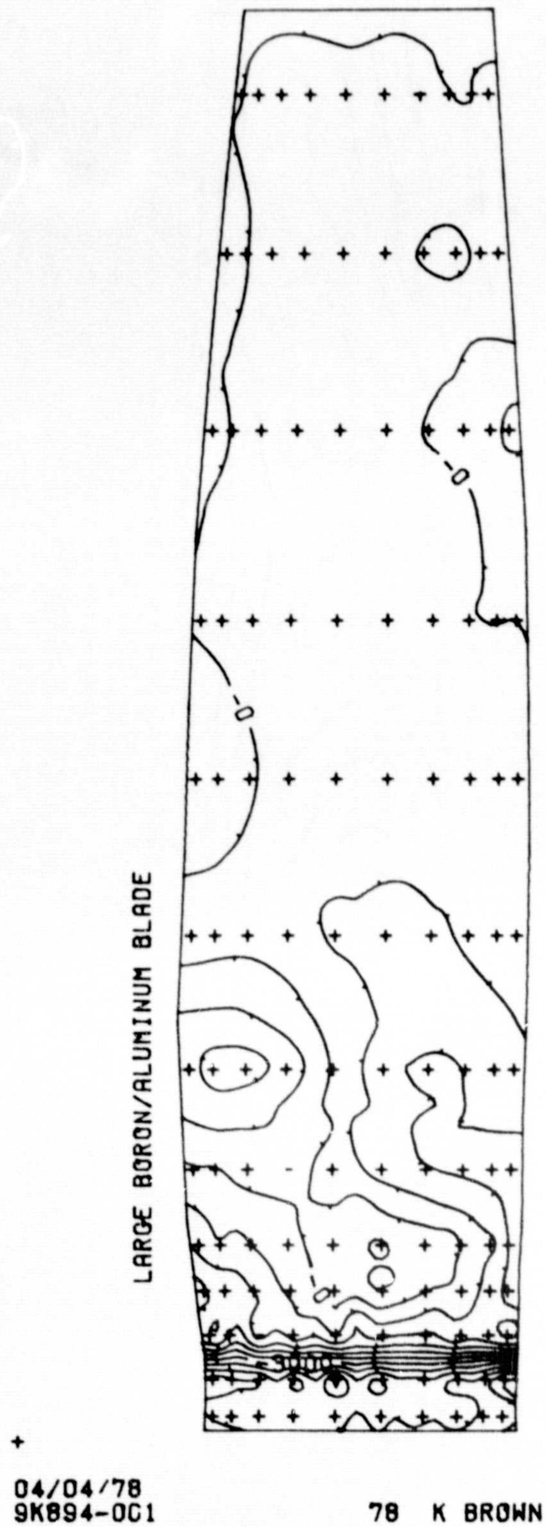

Figure 23. T13 (Radial Shear)
Concave Surface.

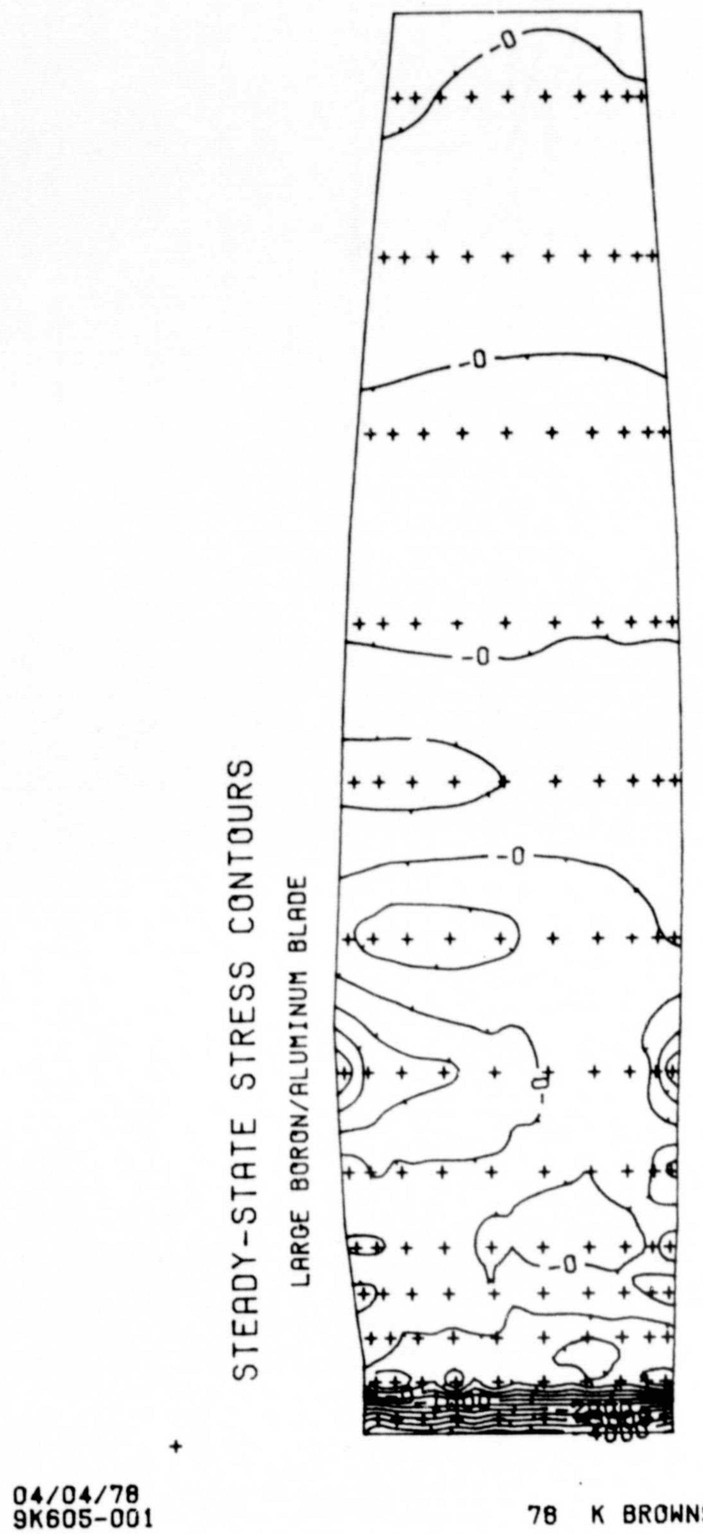

Figure 24. S11 (Thru Thickness)
Convex Surface.

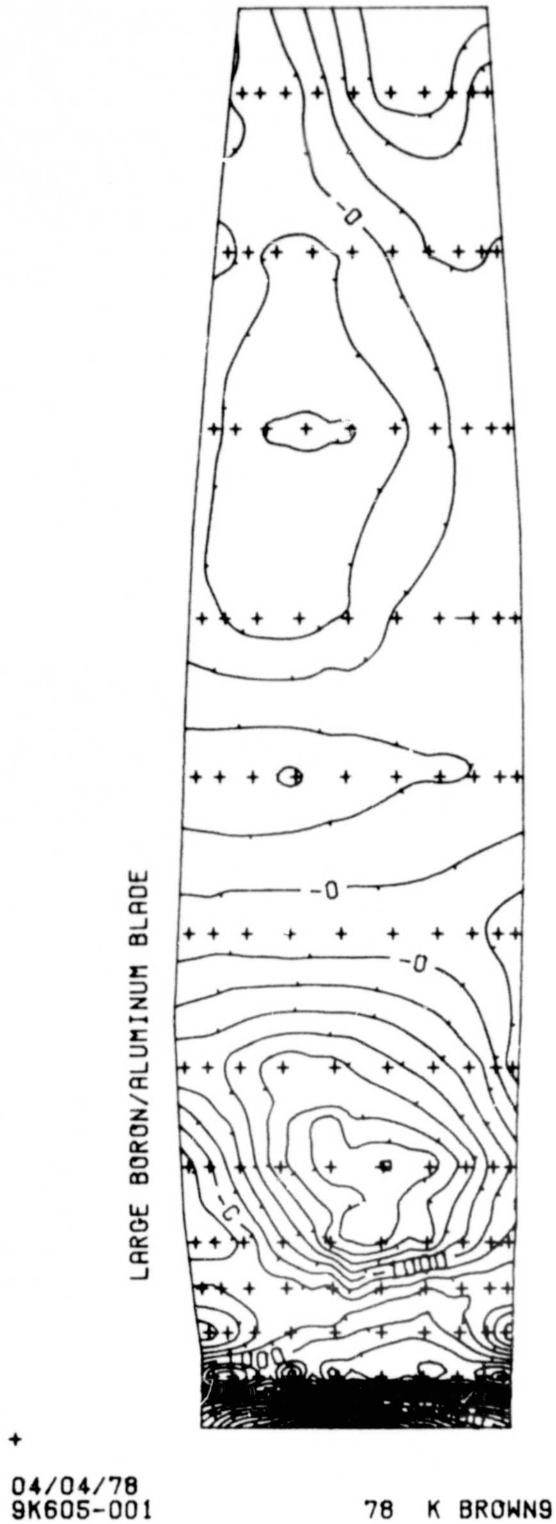

Figure 25. S22 (Chordal) Convex Surface.

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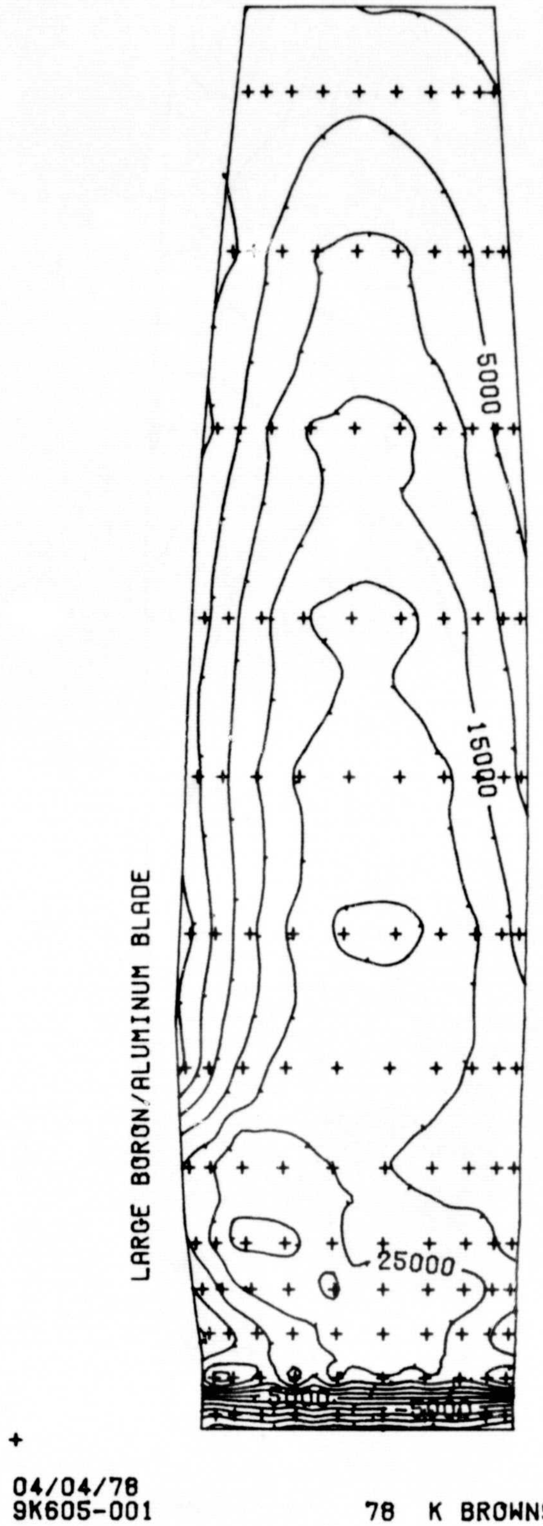

Figure 26. S33 (Radial) Convex Surface.

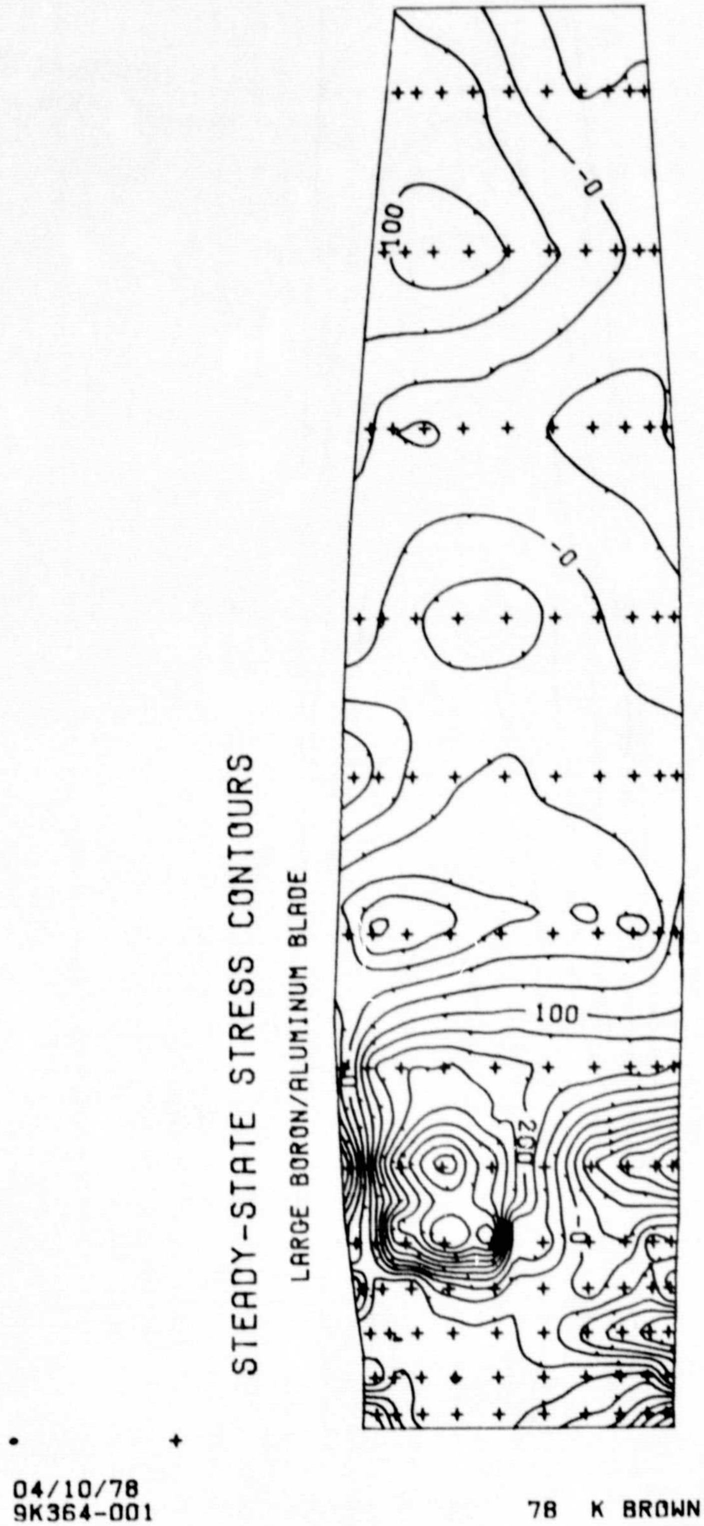

Figure 27. T12 (Chordal Shear)
Convex Surface.

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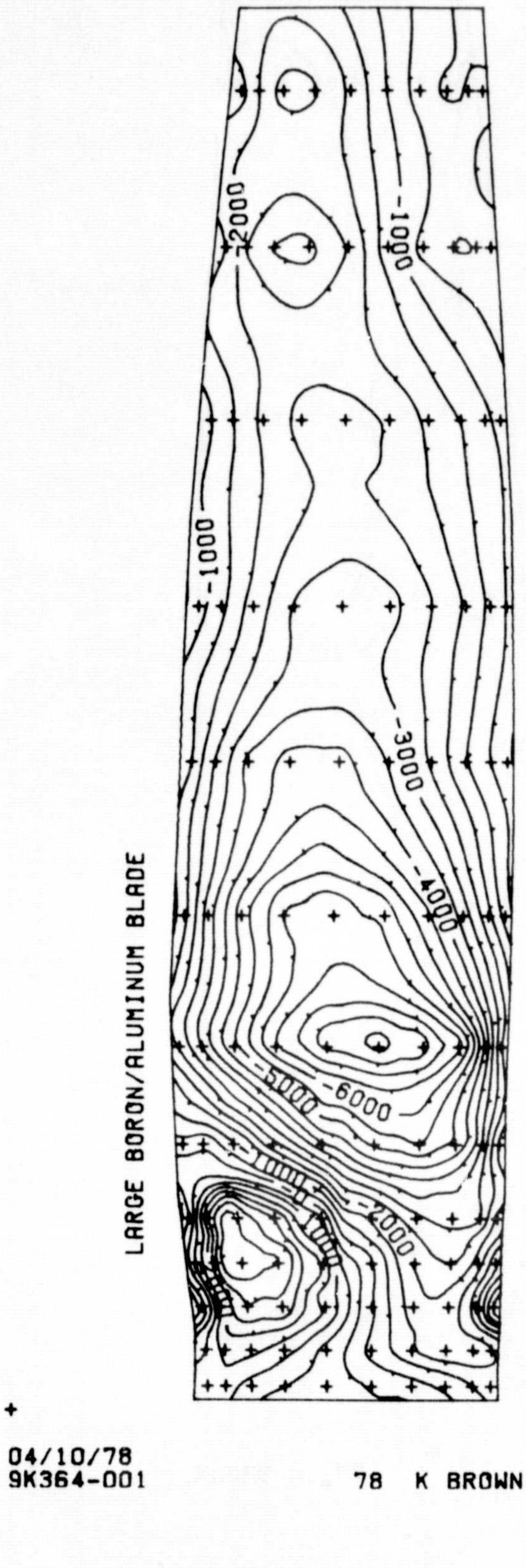


Figure 28. T23 (Cross Fiber Shear)
Convex Surface.

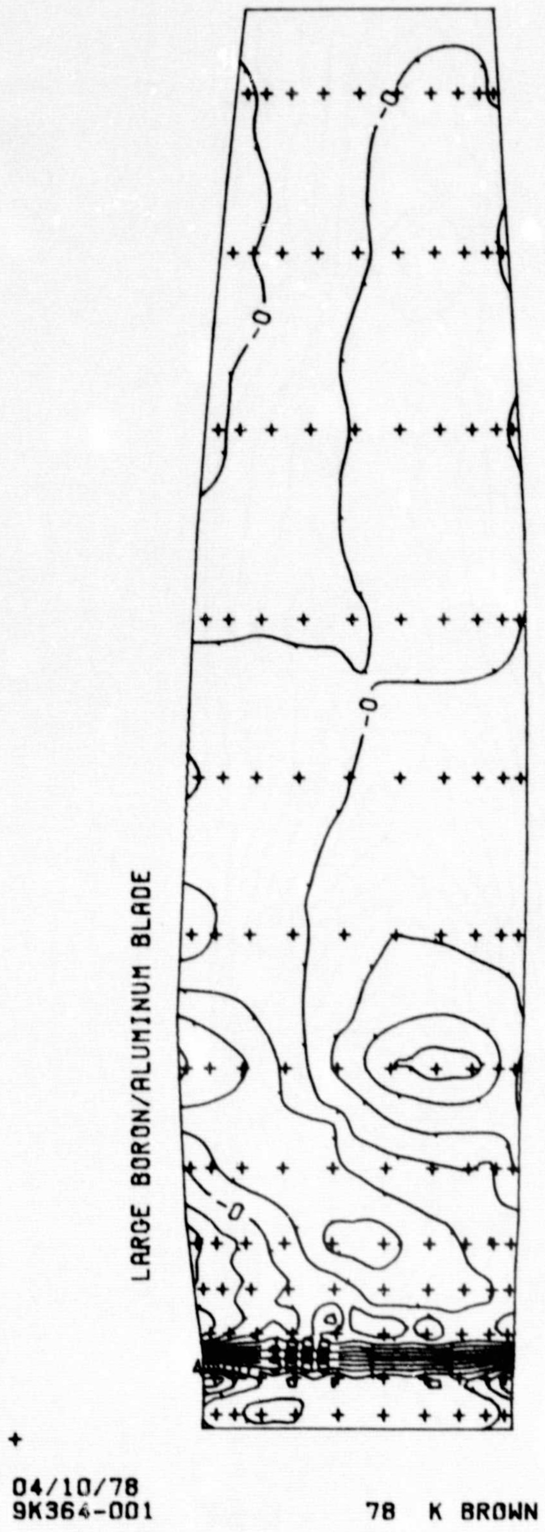


Figure 29. T13 (Radial Shear)
Convex Surface.

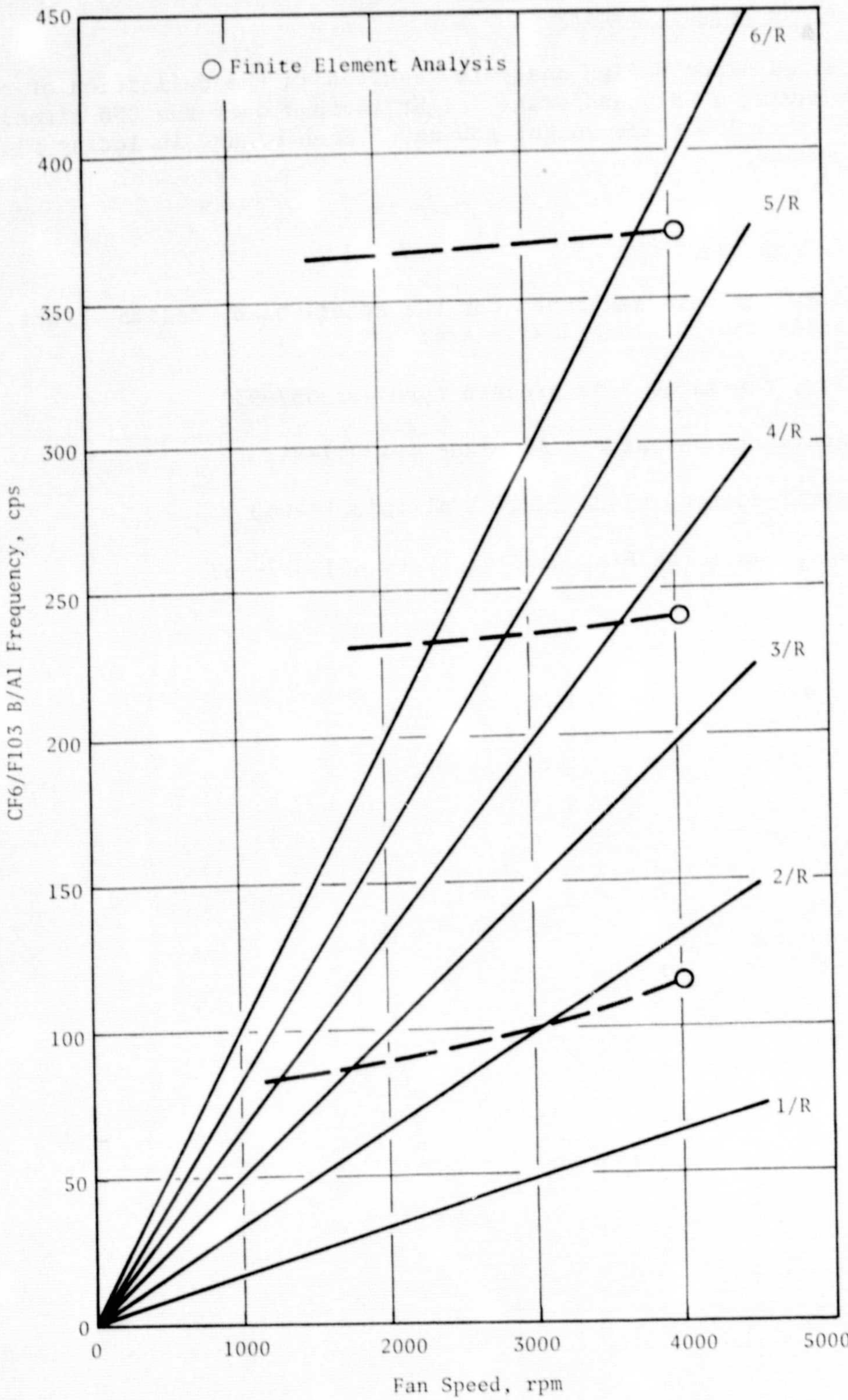


Figure 30. B/Al Fan Blade Frequency.

4.2.5 Blade Weight Summary

The detailed blade design analysis resulted in the definition of a 36-blade design having a 68 pound stage weight savings over the CF6 titanium design. This is a 16% stage weight savings. Each blade, including platform, weighs 9.72 pounds.

4.3 BLADE DETAILED DRAWINGS

Detail drawings were generated for the detail blade design effort. Four drawings defining the 36 blade design are:

1. Blade, fan-large B/Al pressed form 4013057-959

2. Shank sections large B/Al blade 4013057-961

3. Airfoil contour blade large B/Al 4013057-960

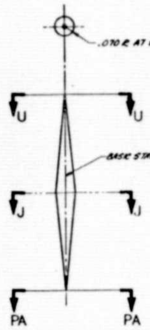
4. Blade, fan large B/Al machined form 4013057-962

TABLE 1

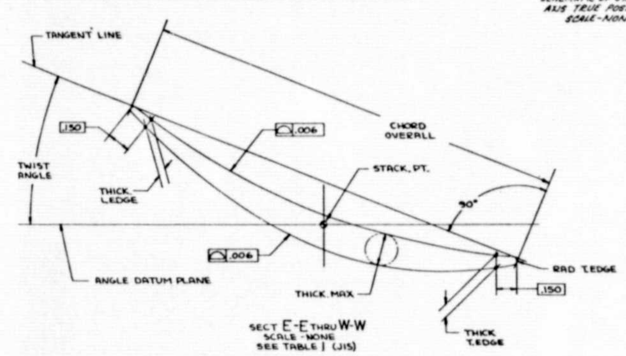
SECT	AIRFOIL SECTION HEIGHT	TWIST ANGLE ±0°30'	THICKNESS LEAD ±.008	THICKNESS MAX ±.010	THICKNESS TRAIL ±.008	CHORD OVERALL ±.020	RADIUS TRAIL EDGE REF	ENGINEERING MASTER NO. 4013057-960
MIN INSP SECT E-E, G-G, J-J, L-L, P-P, S-S & U-U								
A-A	1.865	—	—	.720	—	—	—	SHT 9
B-B	2.141	—	—	.716	—	—	—	9
C-C	3.128	—	—	.700	—	—	—	8
D-D	5.131	—	.163	.676	—	—	—	8
E-E	5.858	10°49'	.155	.667	.175	7.085	.078	7
F-F	7.803	17°56'	.133	.644	.157	7.368	.068	7
G-G	11.283	28°50'	.122	.611	.154	7.879	.064	7
H-H	12.204	31°0'	.121	.597	.153	8.019	.064	6
J-J	14.150	35°2'	.119	.562	.148	8.295	.062	6
K-K	16.606	39°42'	.116	.512	.144	8.648	.061	6
L-L	17.782	41°48'	.115	.487	.141	8.809	.061	5
M-M	18.859	43°50'	.114	.461	.138	8.967	.060	5
N-N	20.489	47°19'	.112	.420	.135	9.197	.058	5
P-P	21.872	50°25'	.110	.387	.131	9.393	.056	4
R-R	22.953	52°39'	.108	.363	.128	9.552	.056	3
S-S	24.898	55°58'	.106	.323	.123	9.828	.054	3
T-T	25.768	57°13'	.105	.307	.121	9.939	.054	3
U-U	26.649	58°30'	.103	.295	.118	10.074	.052	2
V-V	27.969	60°44'	.102	.291	.115	10.349	.052	2
W-W	29.300	63°29'	.100	.292	.111	10.666	.050	1
X-X	1.000	—	—	—	—	—	—	10
AC-AC REF	2.196	—	—	—	—	—	—	10

TABLE 2

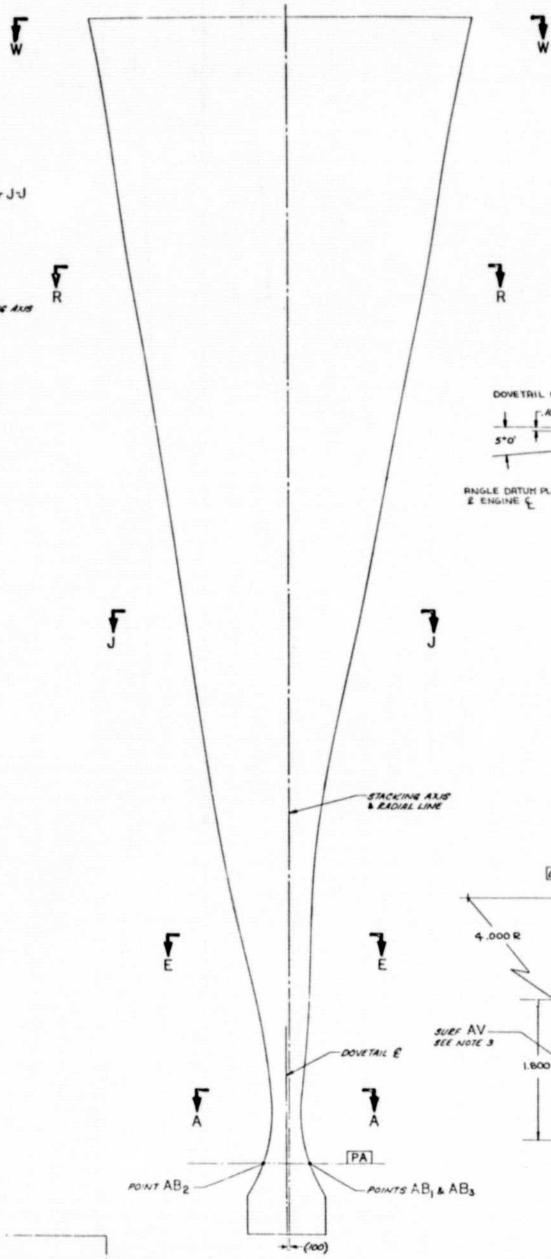
SECT	ENGINEERING MASTER NO. 4013057-961
A1	SHT 2
A2	1
A3	1
A4	2
A5	1
A6	1
A7	2

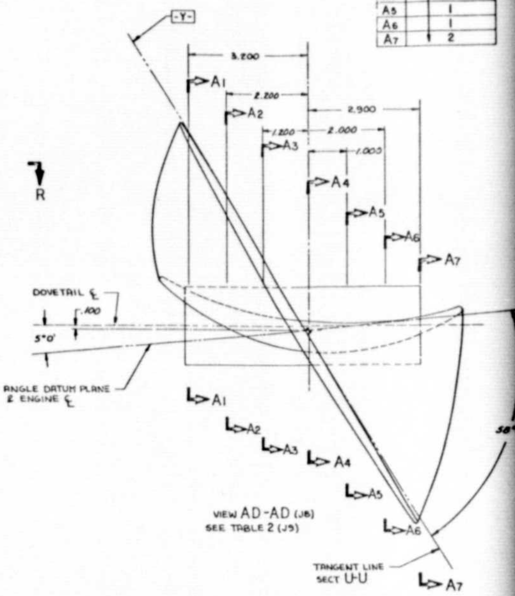


SECT AF-AF (A7)
SCHEMATIC OF STACKING AXIS TRUE POSITION
SCALE-NONE



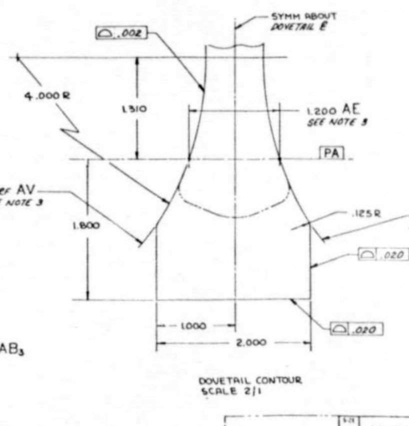
SECT E-E THRU W-W
SCALE-NONE
SEE TABLE 1 (J15)





VIEW AD-AD (J8)
SEE TABLE 2 (J9)

PART IDENT NO
4013057-959P01



DOVETAIL CONTOUR
SCALE 2/1

J | 4013057-959

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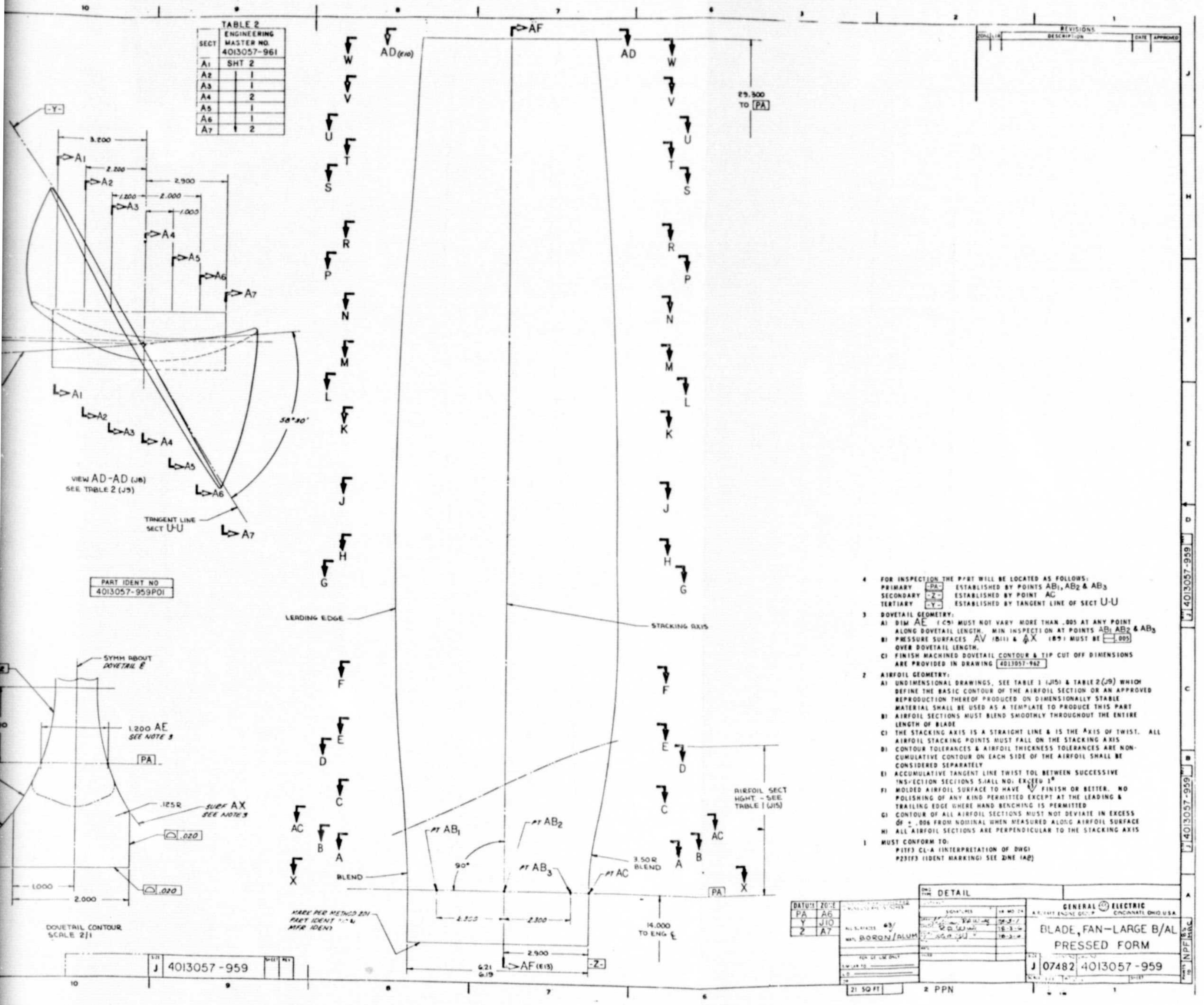

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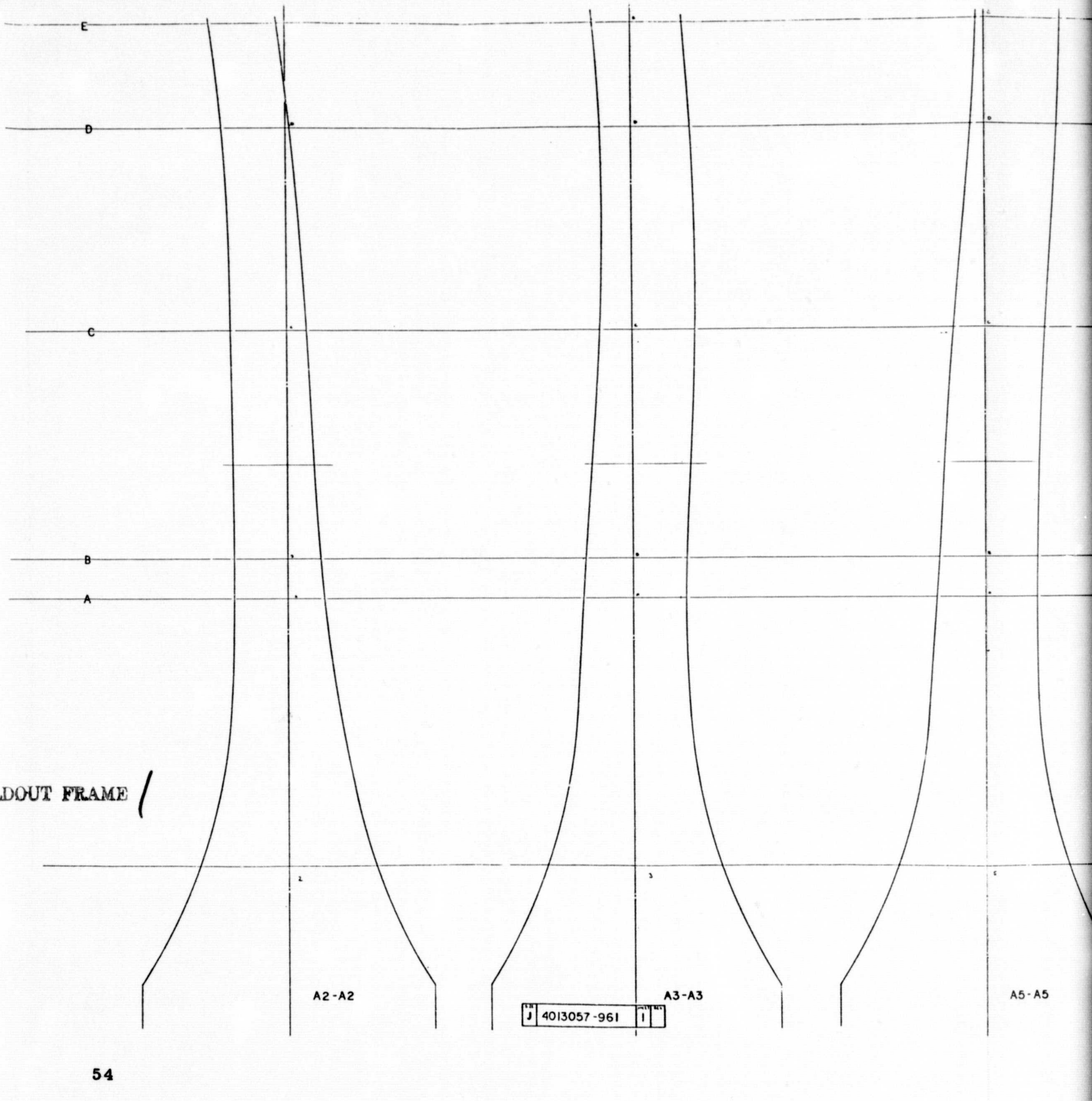

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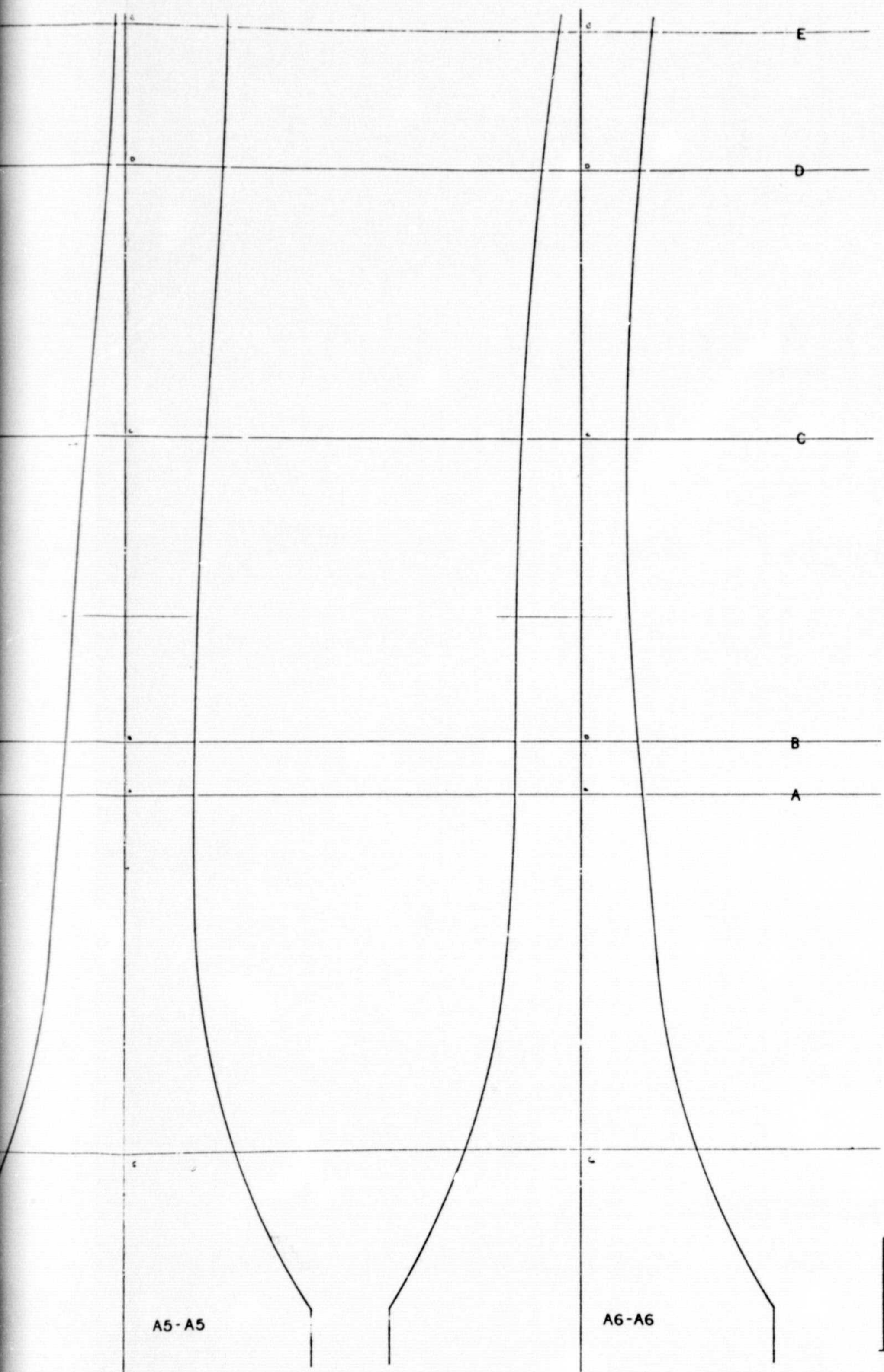

REVISIONS

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4013057-961

ENGRG MASTER

ATMOSPHERIC CONDITIONS
TEMP 72 °F | RH 48 %

CONTOUR

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES

ALL SURFACES ✓

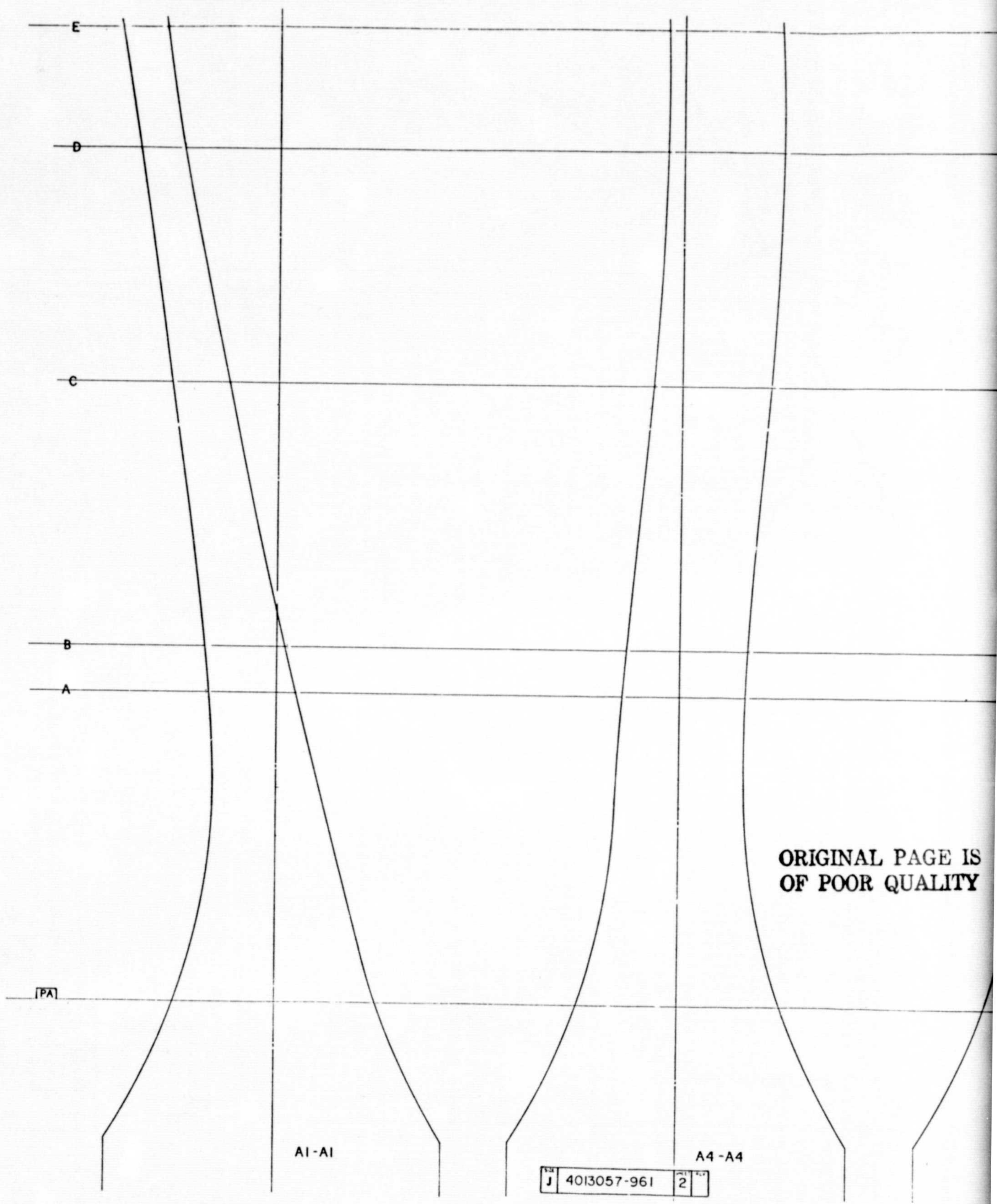
GENERAL ELECTRIC
AIRCRAFT ENGINE GROUP CINCINNATI OHIO U.S.A.

SHANK SECTIONS
LARGE B/AL BLADE

J | 07482 | 4013057-961

SCALE 5/1 SHEET 1 OF 2

UNP



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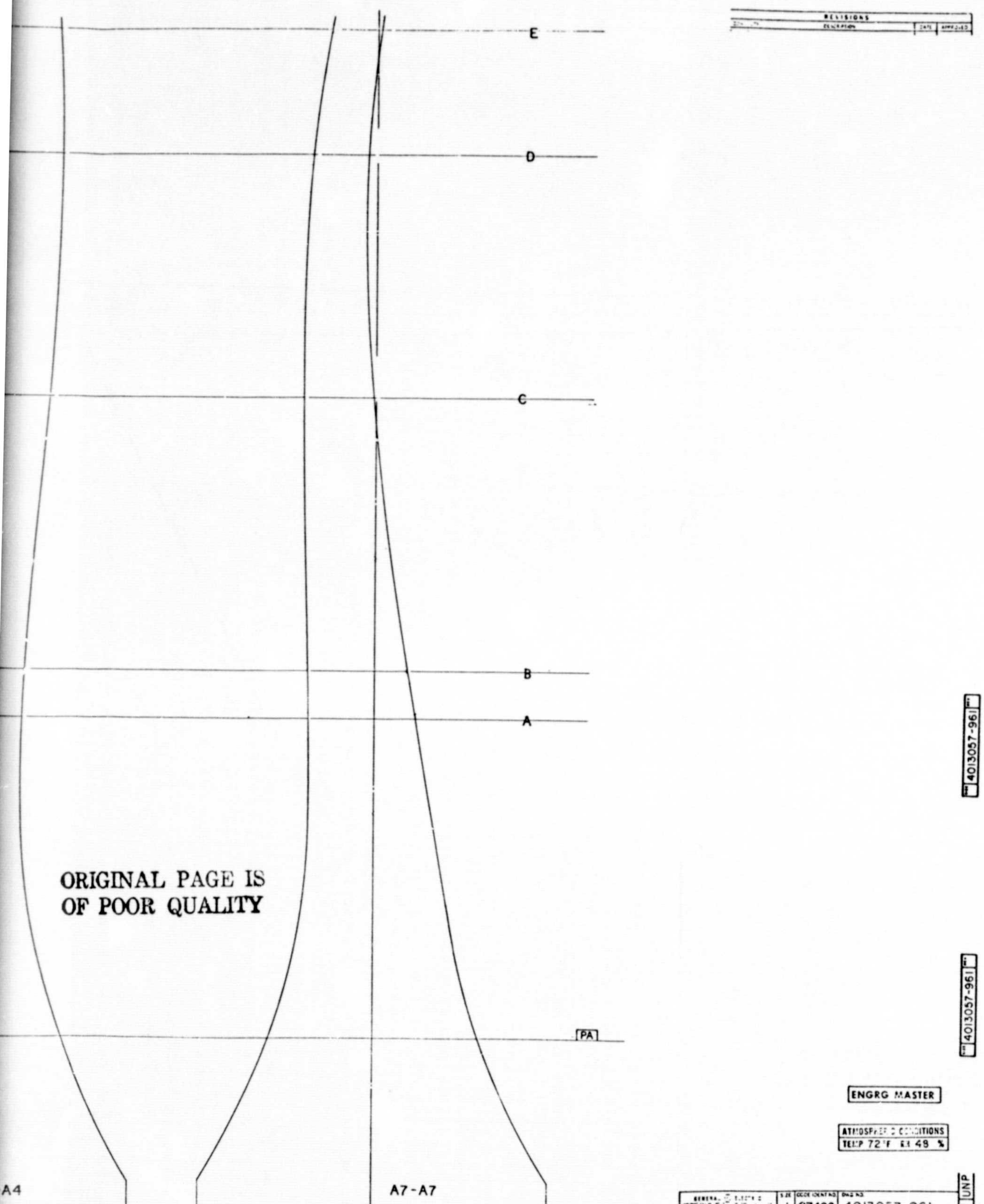

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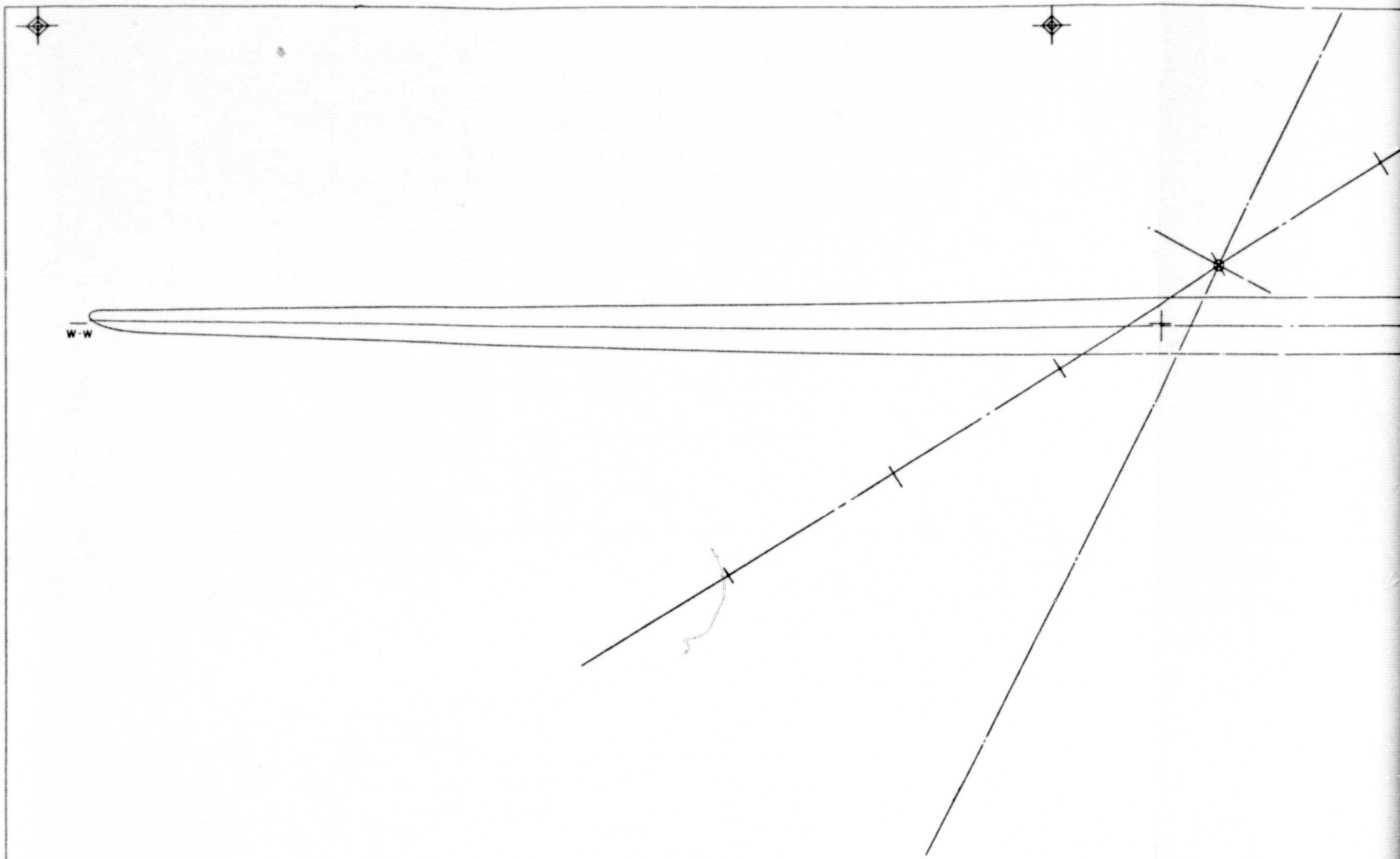

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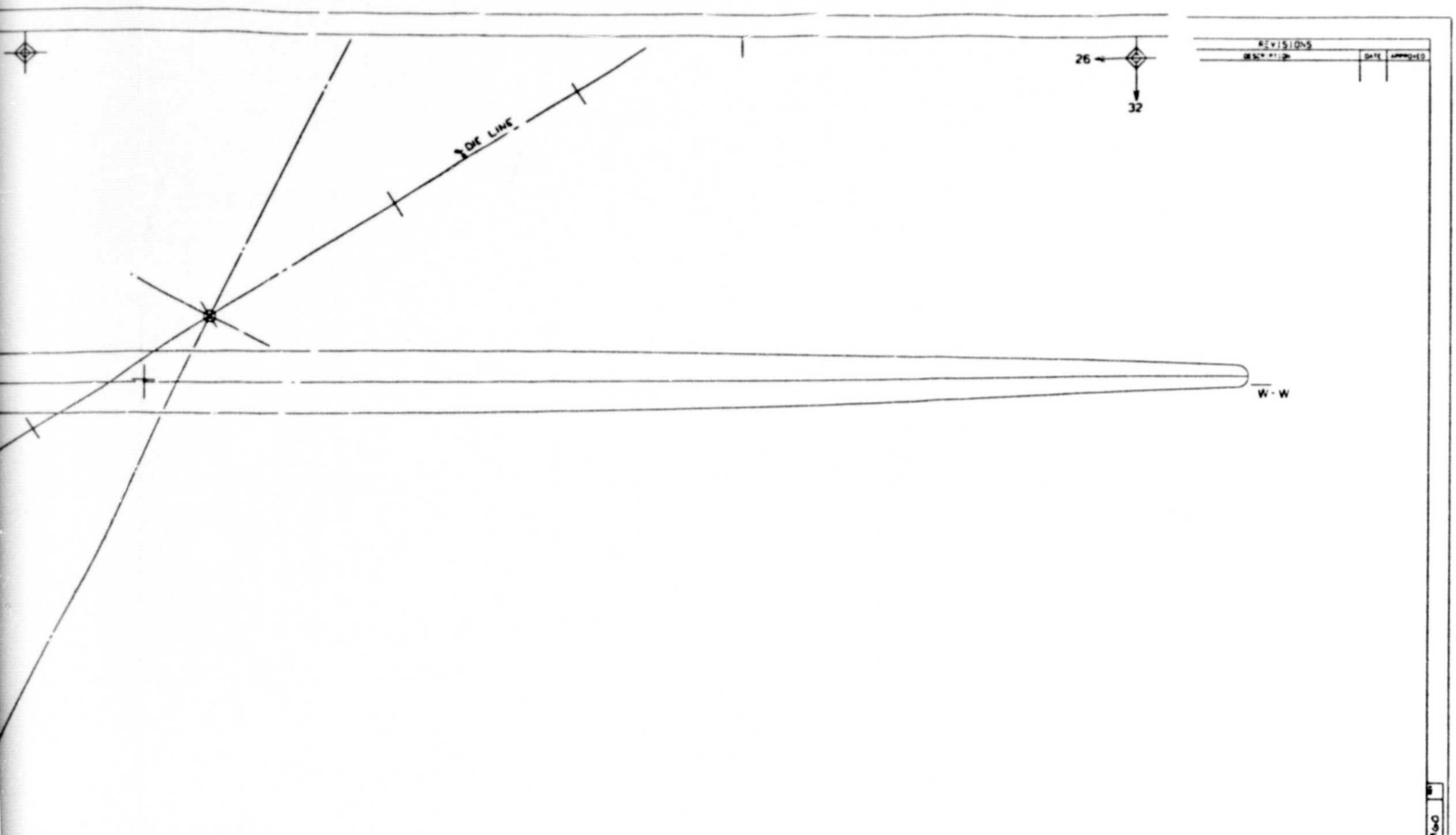
2 INCREMENTAL SPACING OF DIVISIONS ON DIE LINE 1.000

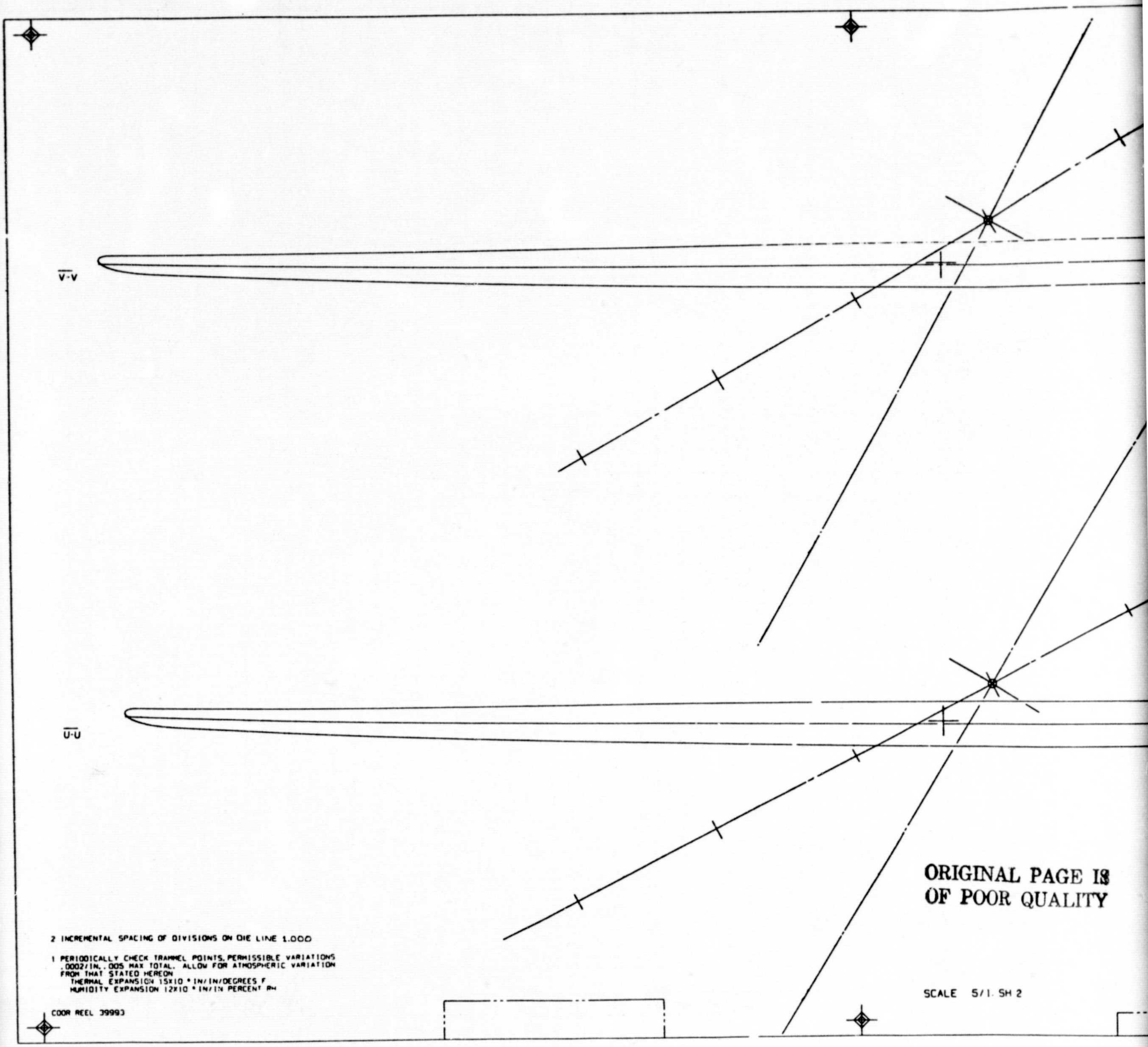
1 PERIODICALLY CHECK TRAMMEL POINTS. PERMISSIBLE VARIATIONS .0002/IN, .005 MAY TOTAL. ALLOW FOR ATMOSPHERIC VARIATION FROM THAT STATED HEREON
THERMAL EXPANSION 15X10 * IN/IN/DEGREES F
HUMIDITY EXPANSION 12X10 * IN/IN PERCENT RH

COOR REEL 39993

SCALE 5/1 SH 1 OF 10



REVISIONS
26
32
W-W
SCALE 5/1 SH 1 OF 10
J 4013057-960
ATMOSPHERIC CONDITIONS
CONTOUR
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
ALL SURFACES
GENERAL ELECTRIC
AIRFOIL CONTOUR
BLADE LARGE B/AL
STAGE 1
J 07482 4013057-960



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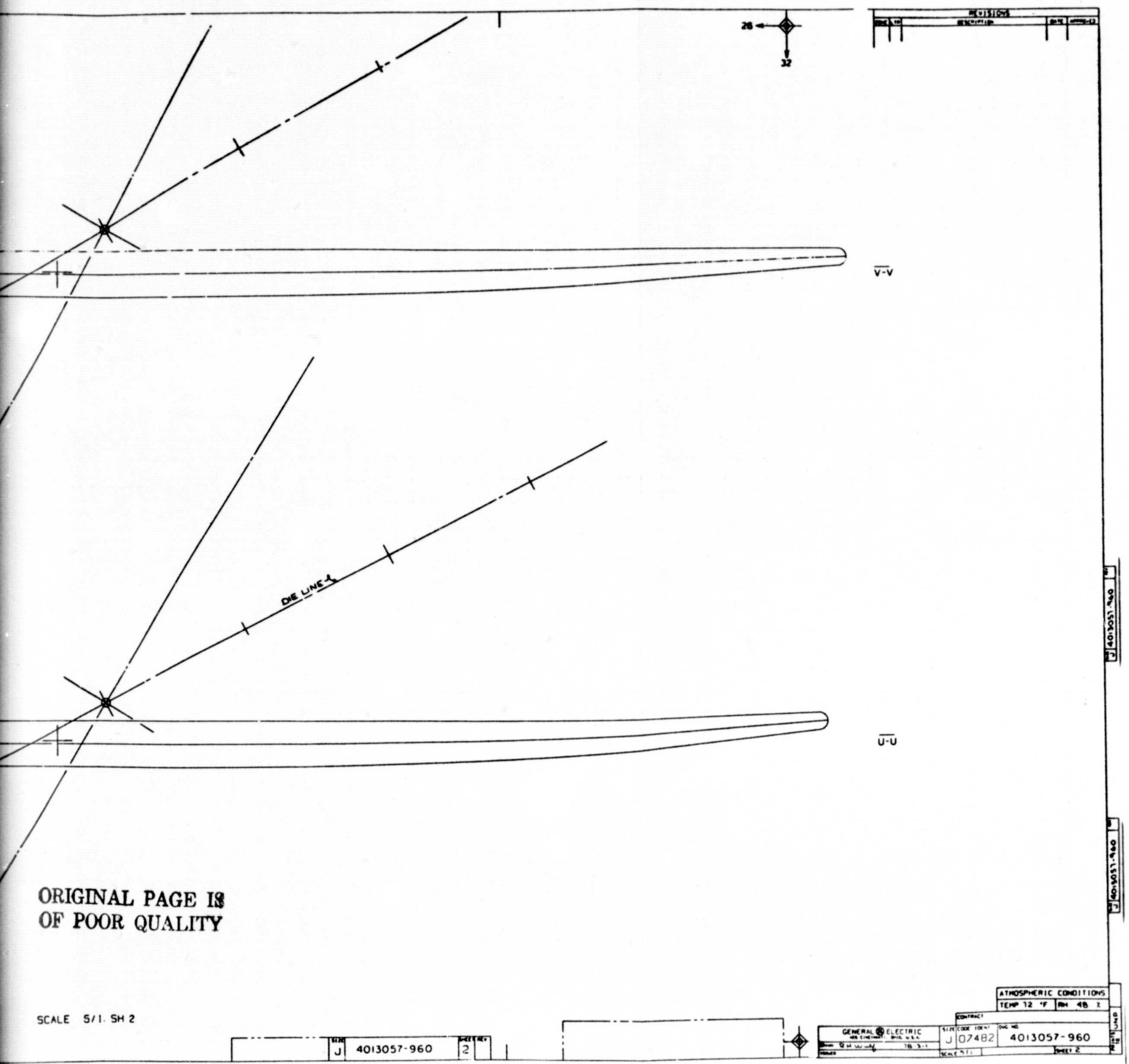

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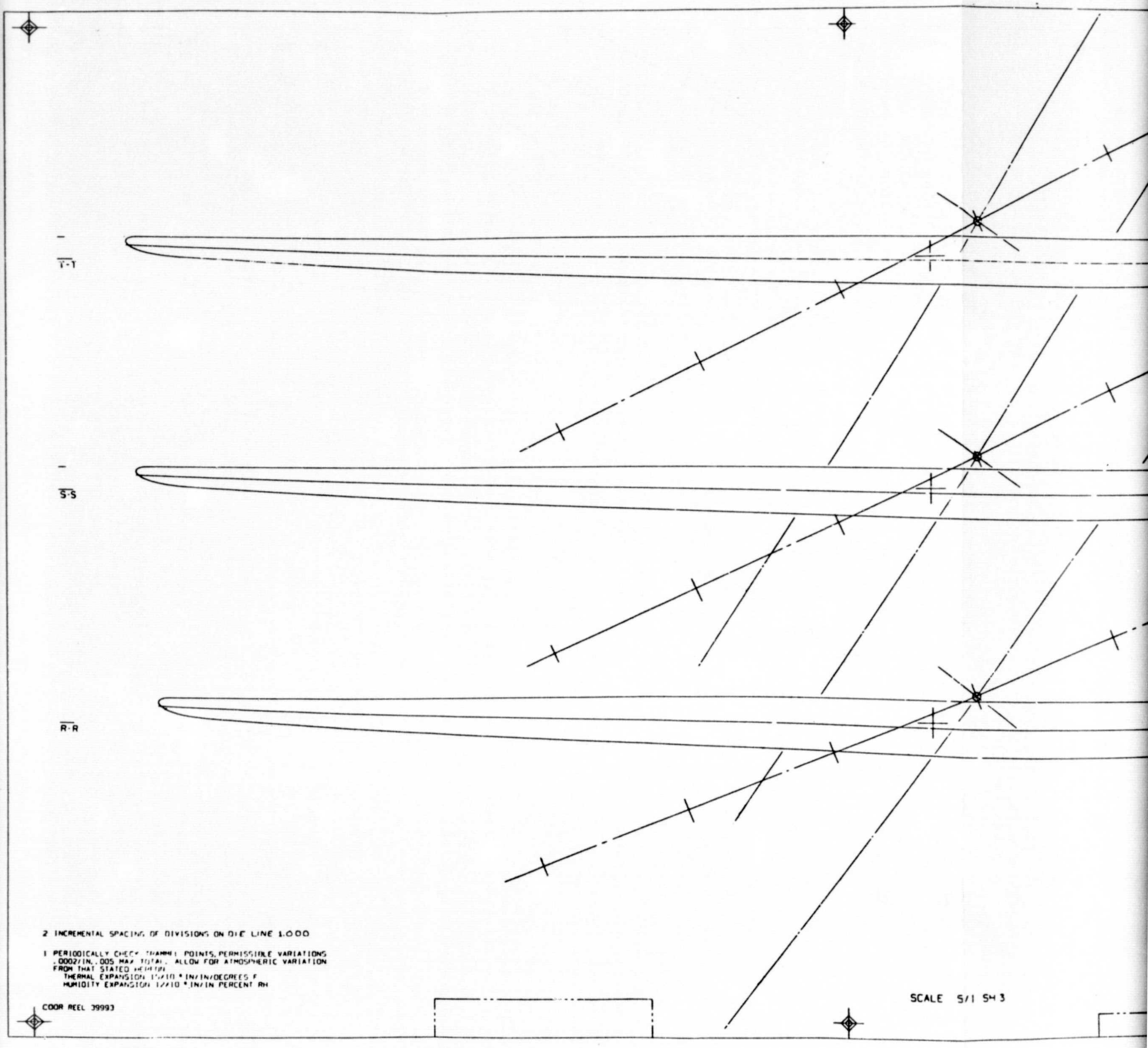

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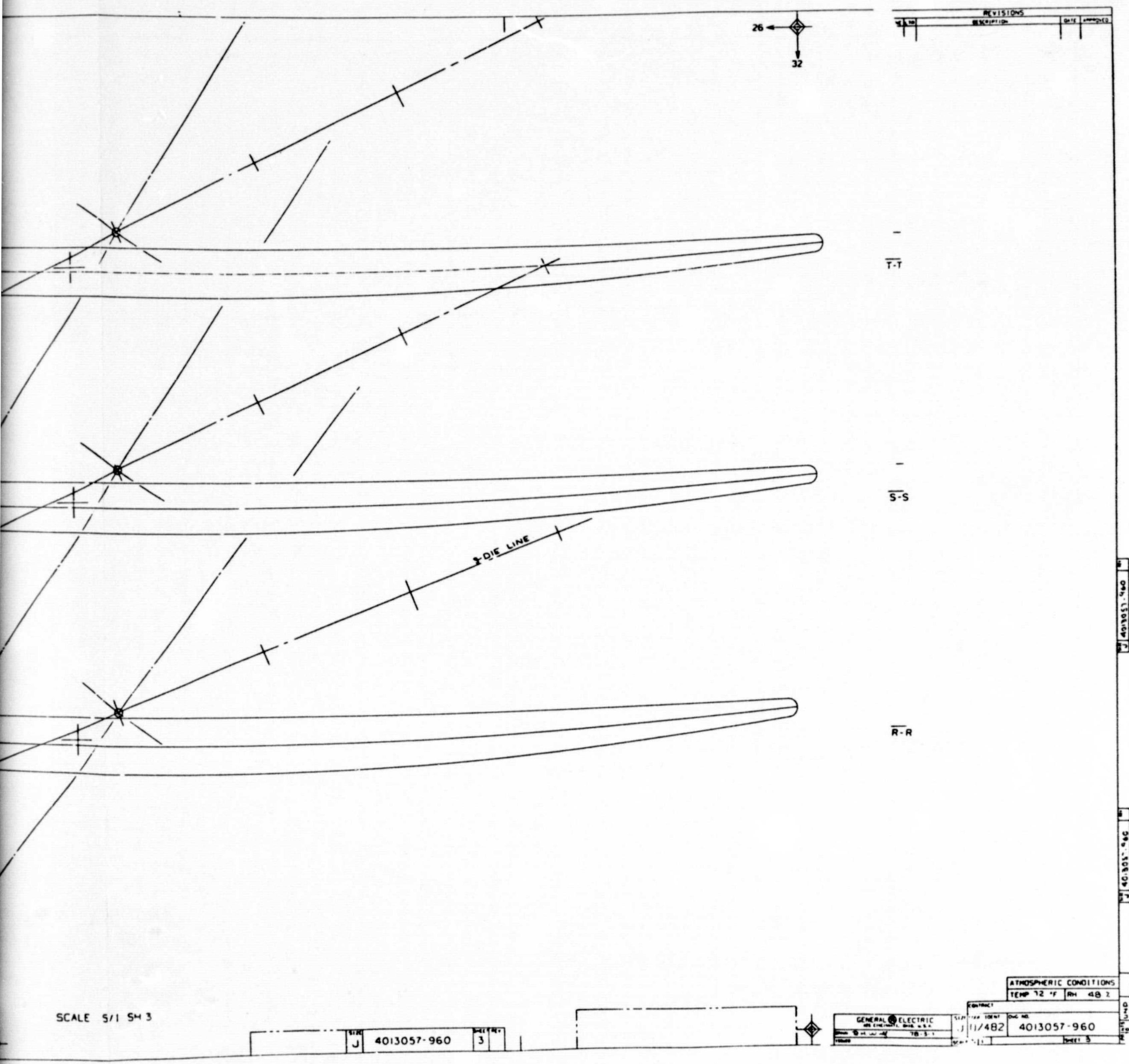

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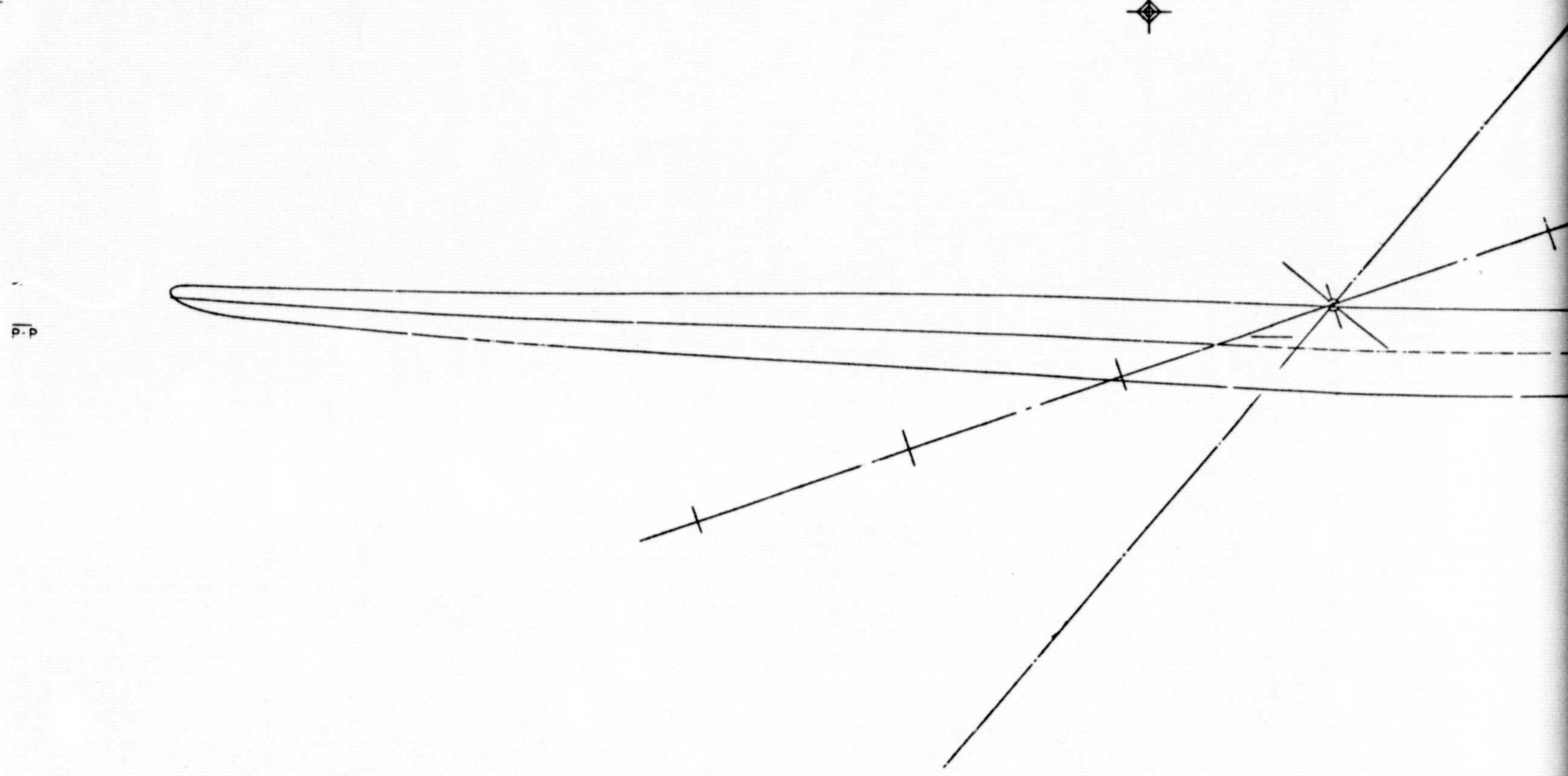

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2 INCREMENTAL SPACING OF DIVISIONS ON DIE LINE 1.000

1 PERIODICALLY CHECK TRAMMEL POINTS, PERMISSIBLE VARIATIONS .0002/IN, .005 MAX TOTAL. ALLOW FOR ATMOSPHERIC VARIATION FROM THAT STATED HEREON
THERMAL EXPANSION 15X10 * IN/IN/DEGREES F
HUMIDITY EXPANSION 12X10 * IN/IN PERCENT RH

COOR REEL 39993

SCALE 5/1 SH 4

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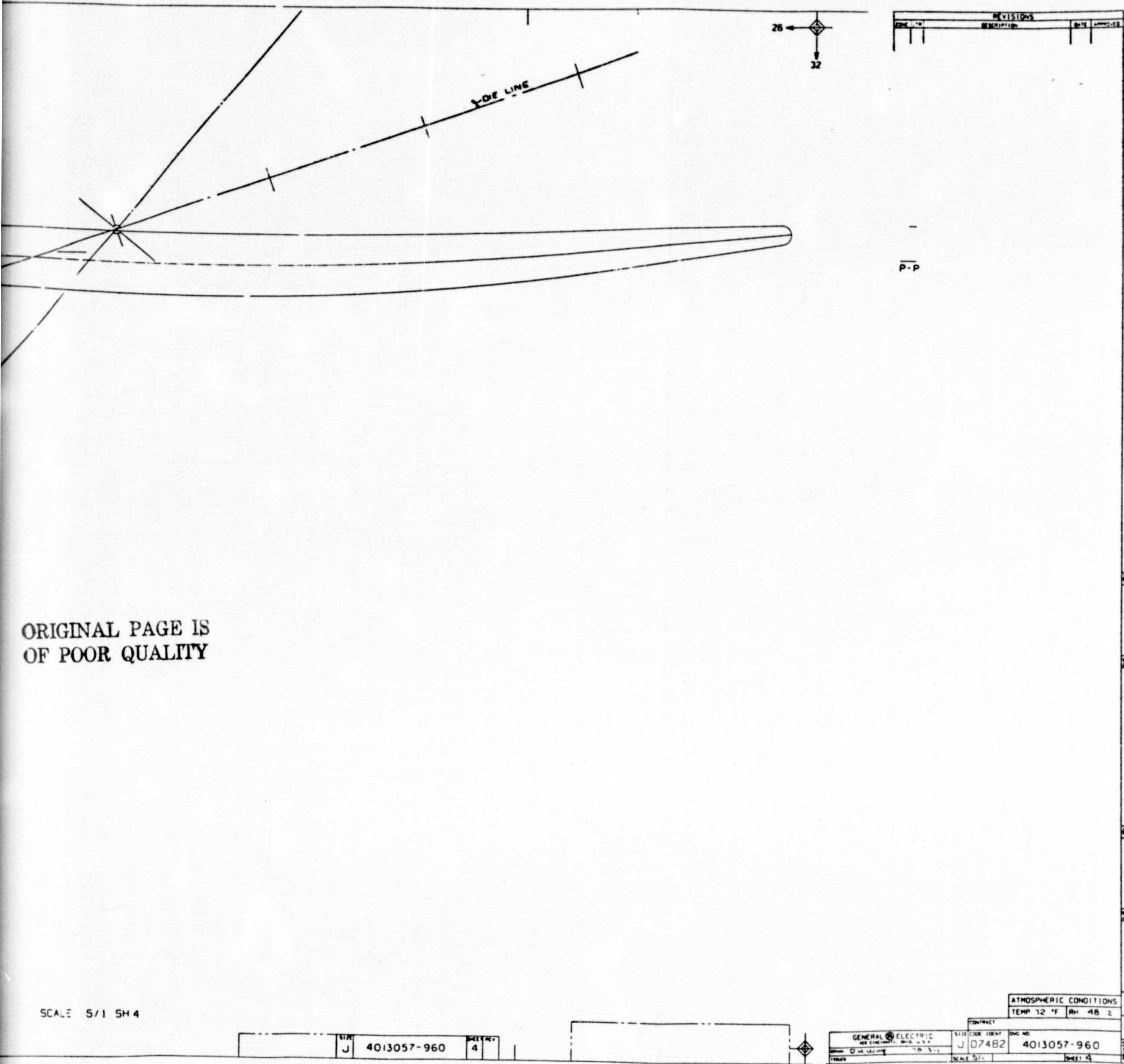

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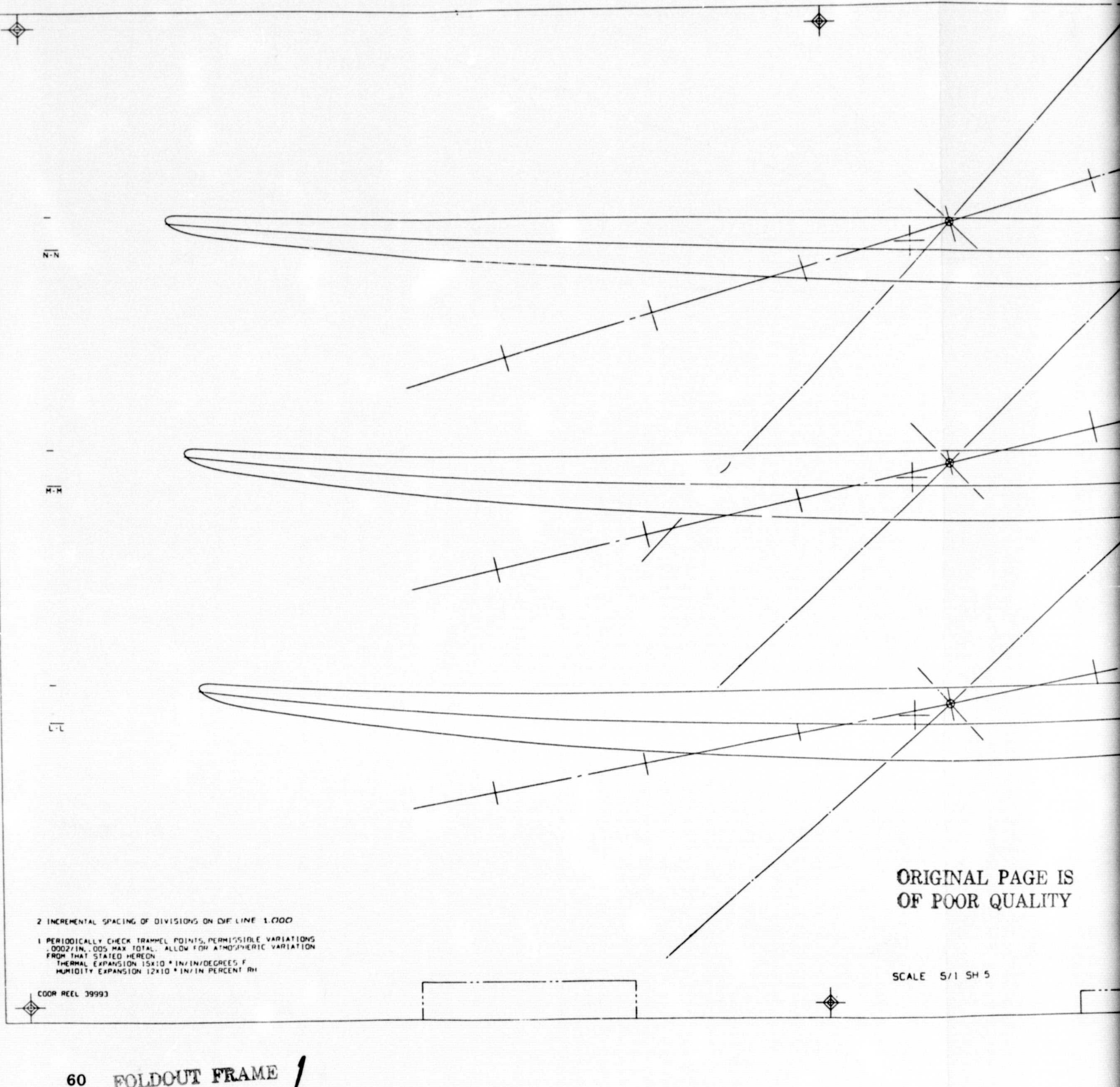

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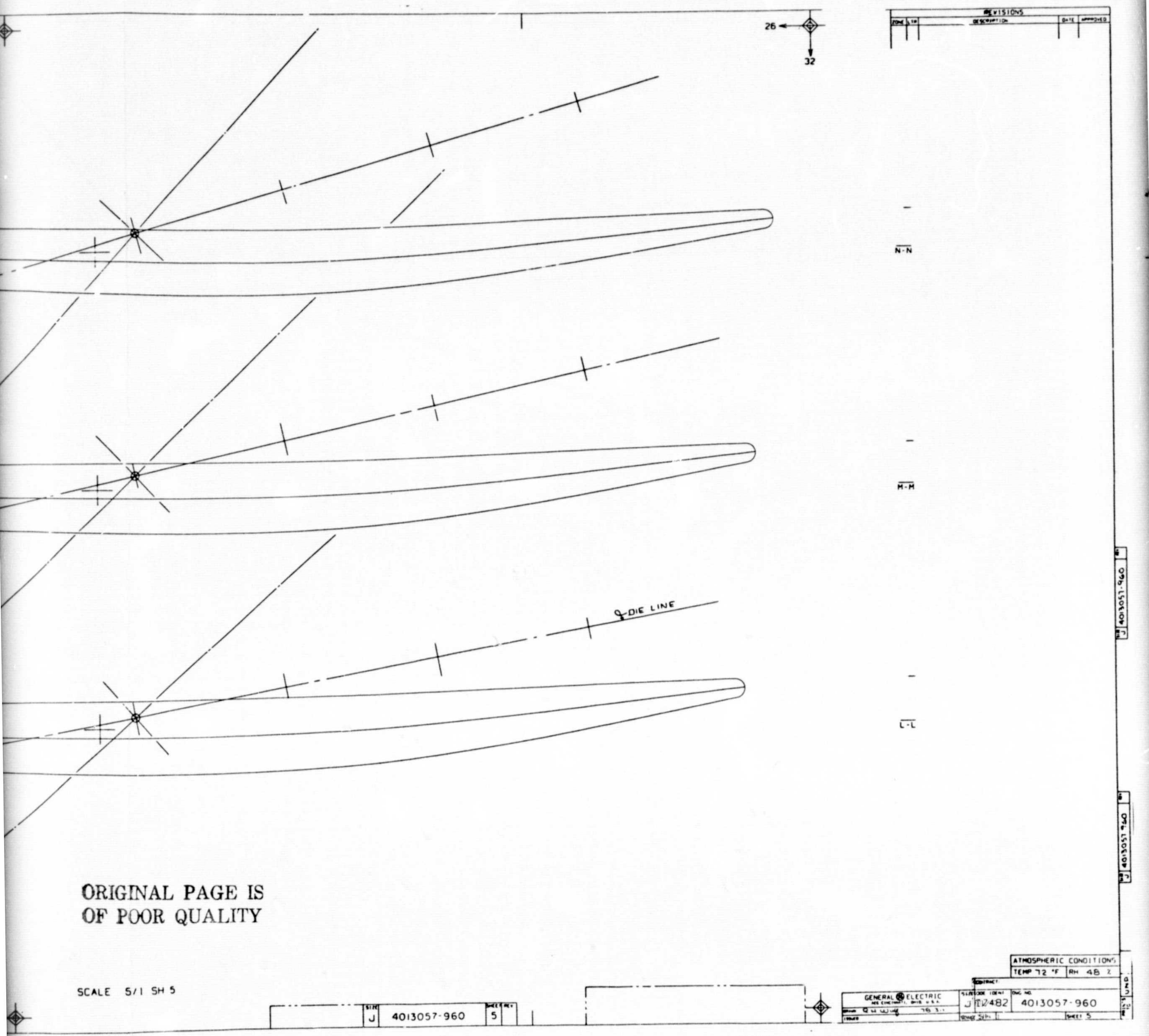

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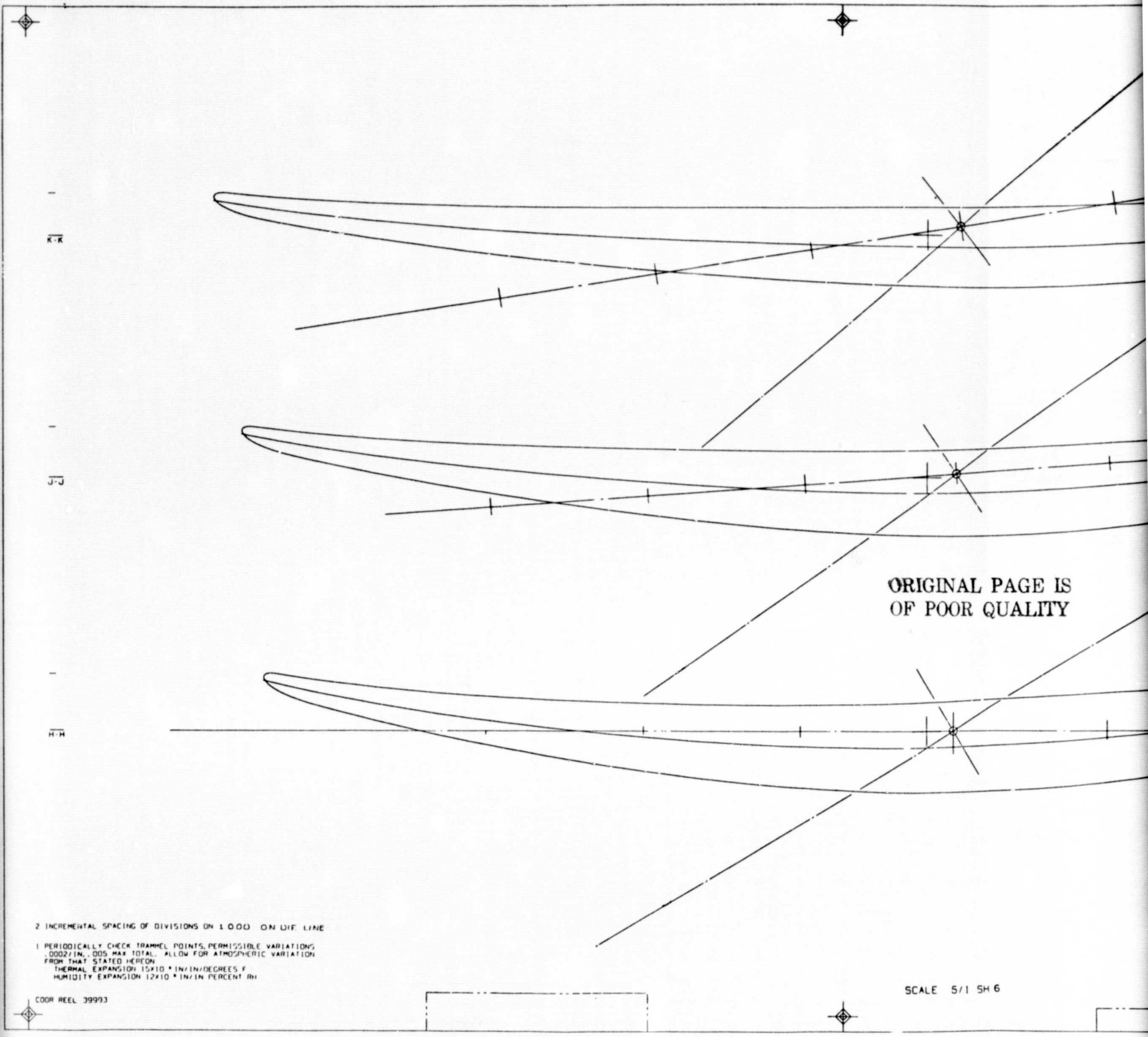

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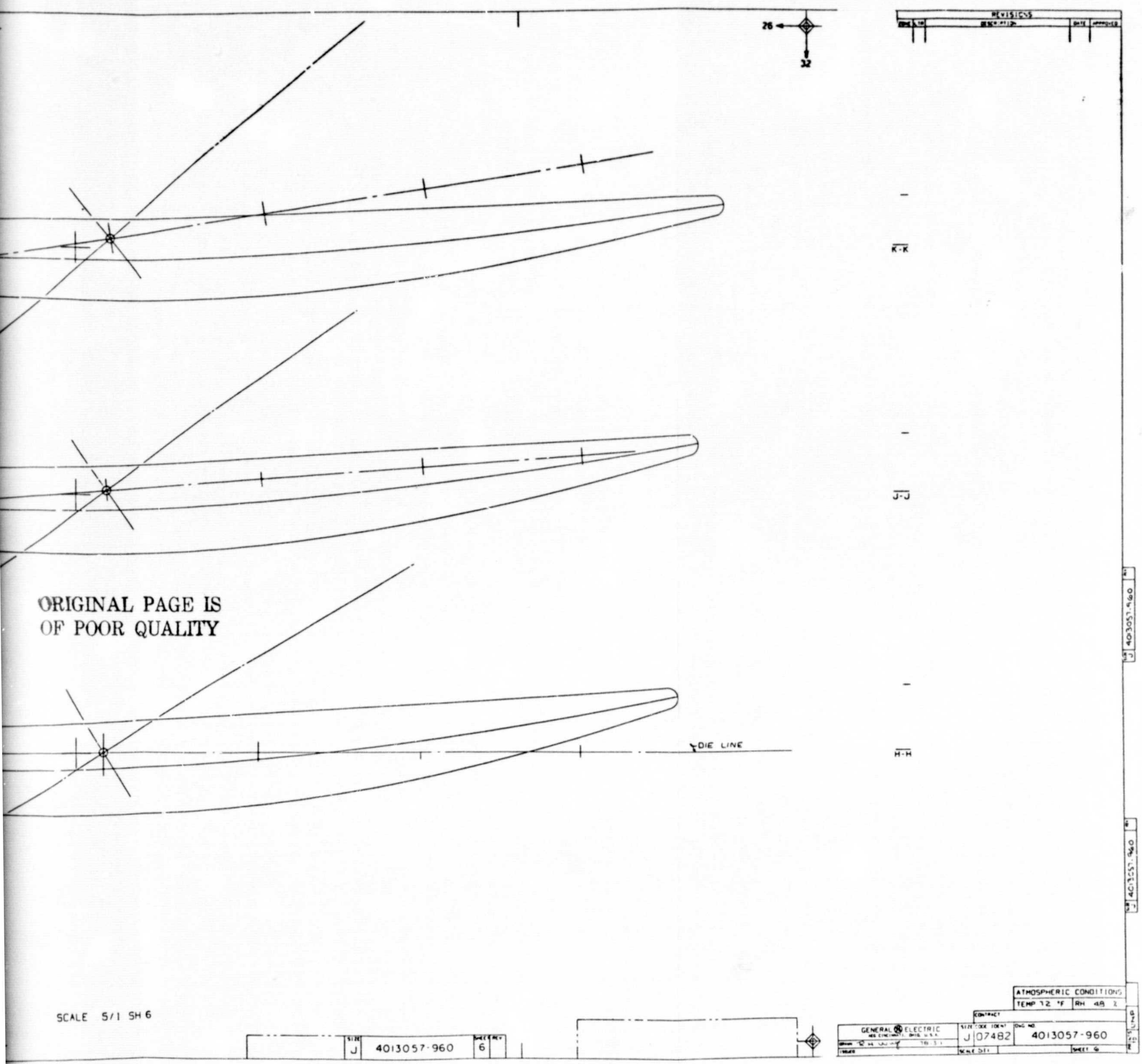

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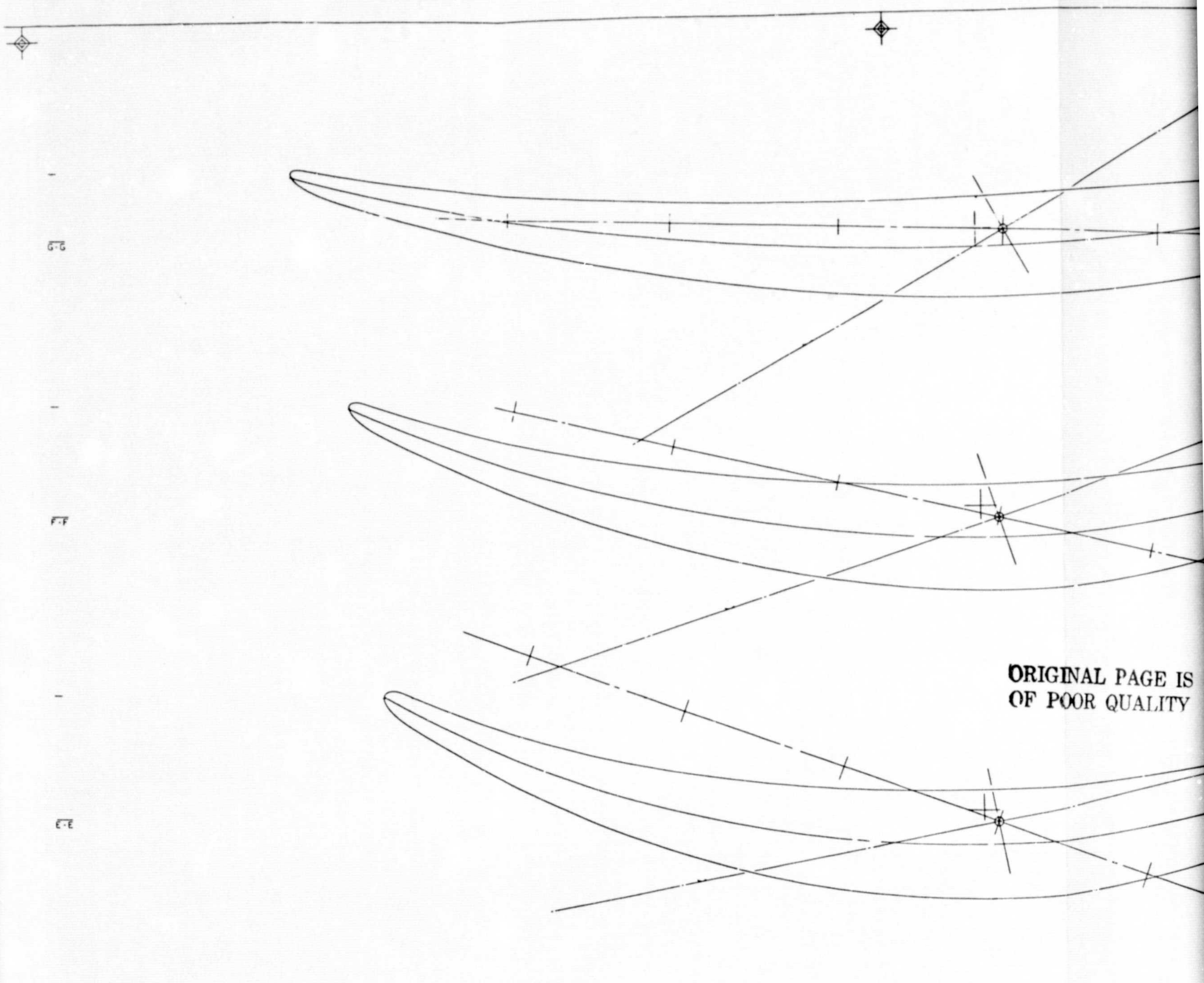

2 INCREMENTAL SPACING OF DIVISIONS ON DIE LINE 1.000

1 PERIODICALLY CHECK TRAMMEL POINTS. PERMISSIBLE VARIATIONS .0002/IN., .005 MAX TOTAL. ALLOW FOR ATMOSPHERIC VARIATION FROM THAT STATED HEREON
THERMAL EXPANSION 15X10 * IN/IN/DEGREES F
HUMIDITY EXPANSION 12X10 * IN/IN PERCENT RH

SCALE 5/1 SH 7

COOR REEL 39993

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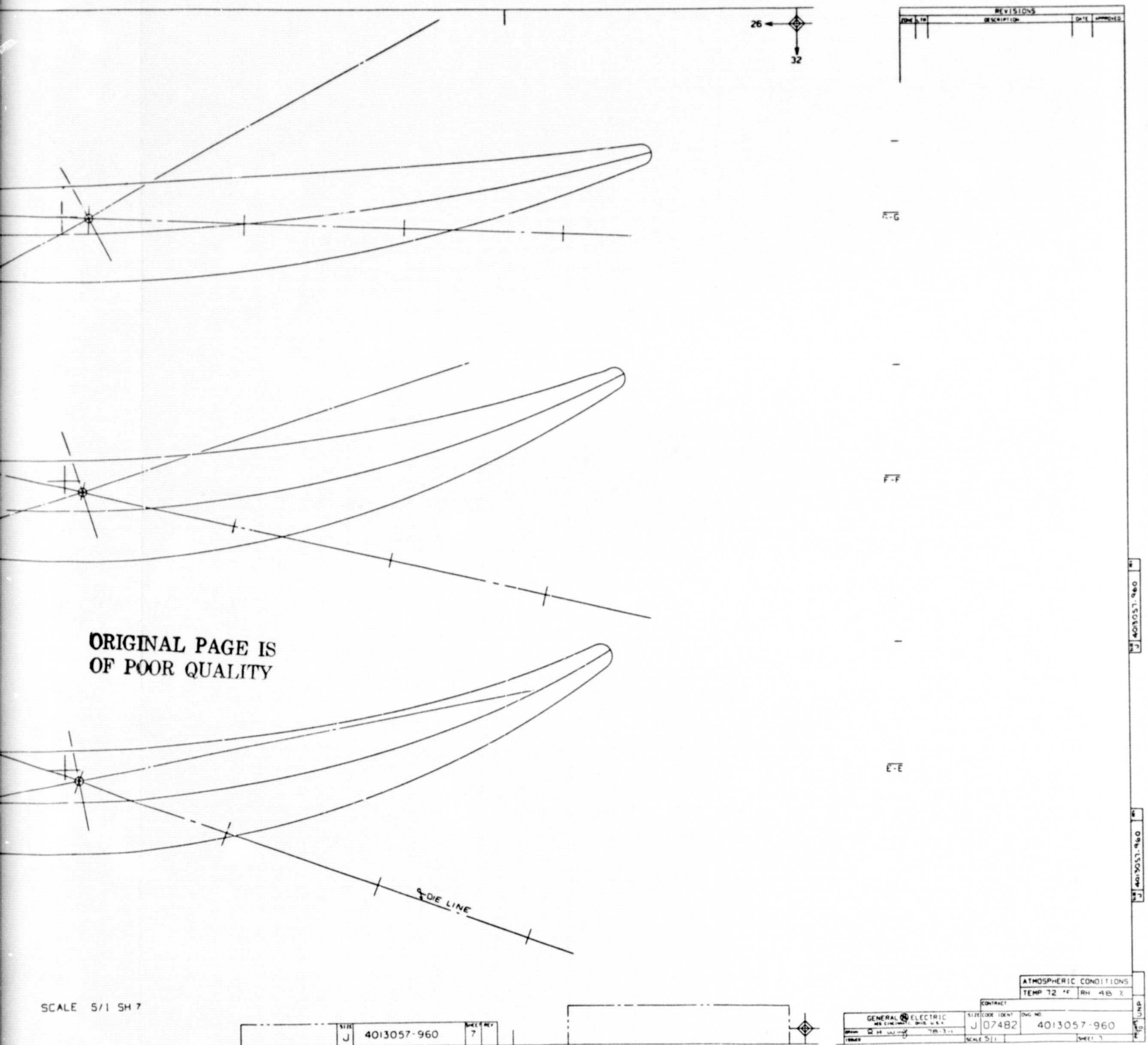

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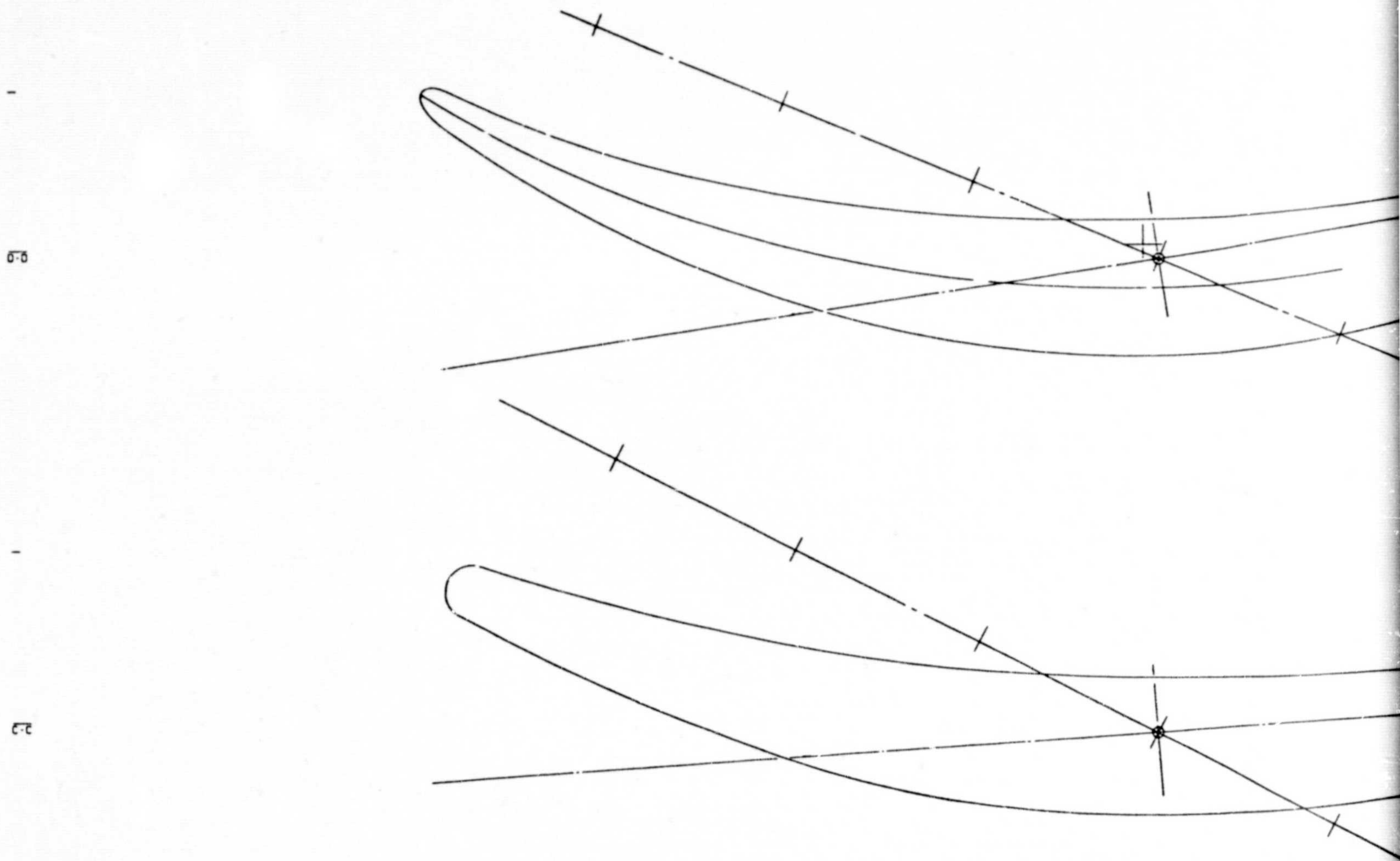

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2 INCREMENTAL SPACING OF DIVISIONS ON DIE LINE 1.000

1 PERIODICALLY CHECK TRAMMEL POINTS, PERMISSIBLE VARIATIONS .0002/IN, .005 MAX TOTAL. ALLOW FOR ATMOSPHERIC VARIATION FROM THAT STATED HEREON
THERMAL EXPANSION 15X10 * IN/IN/DEGREES F
HUMIDITY EXPANSION 12X10 * IN/IN PERCENT RH

SCALE 5/1 SH 8

COOR REEL 39993

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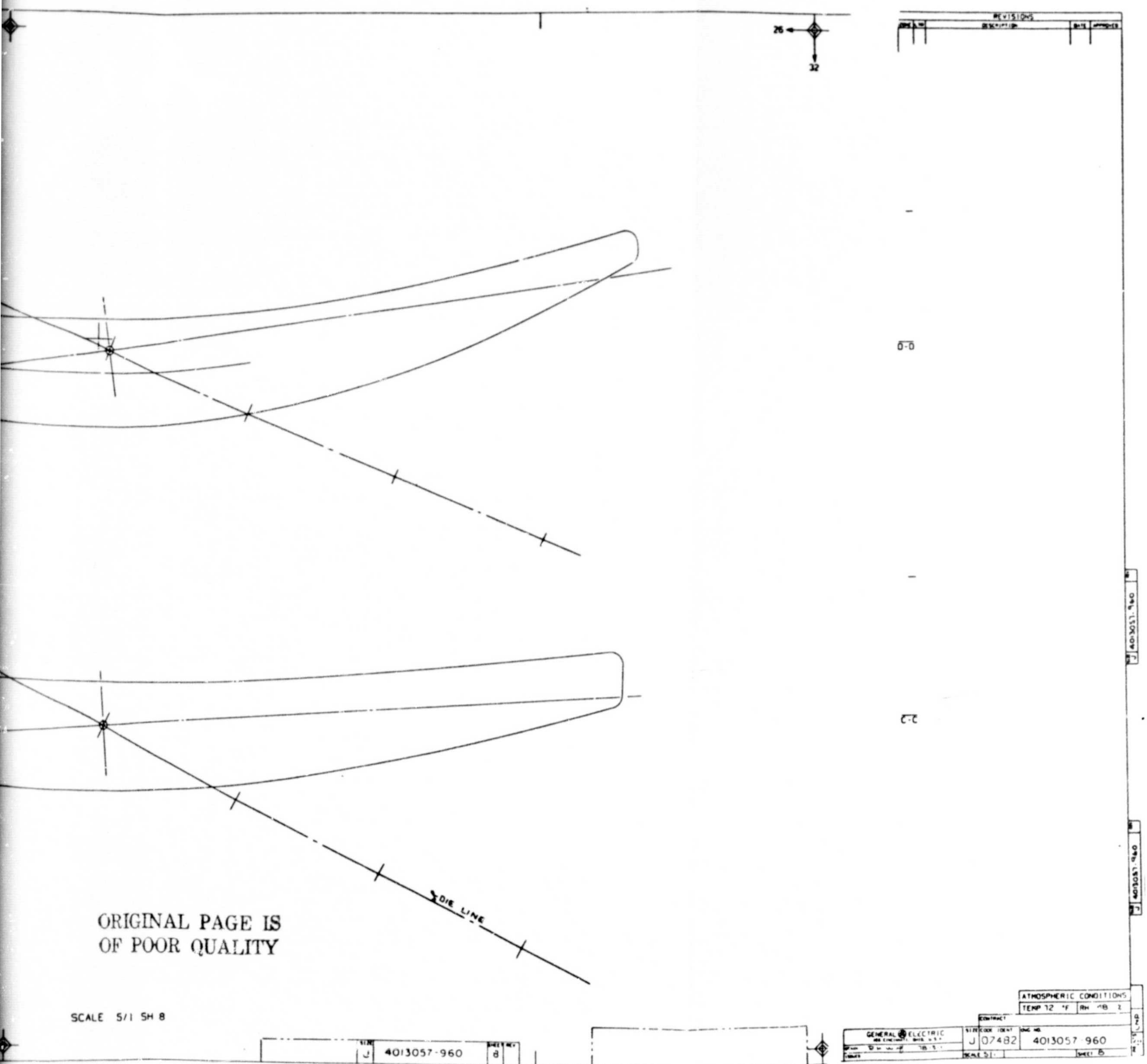
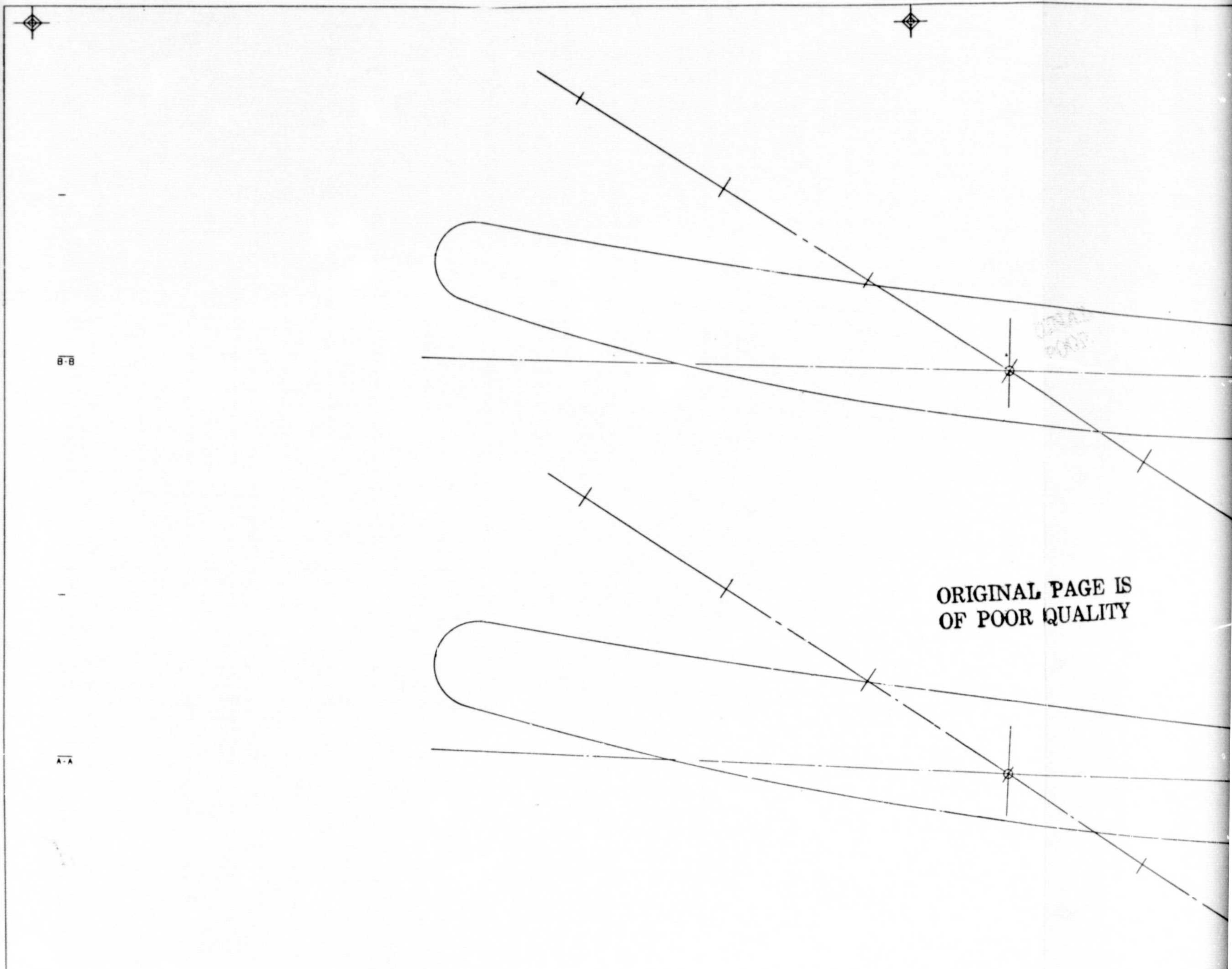

26
32
REVISIONS
D-D
C-C
DIE LINE
SCALE 5/1 SH 8
J 4013057-960 8
ATMOSPHERIC CONDITIONS
GENERAL ELECTRIC
J 07482 4013057-960

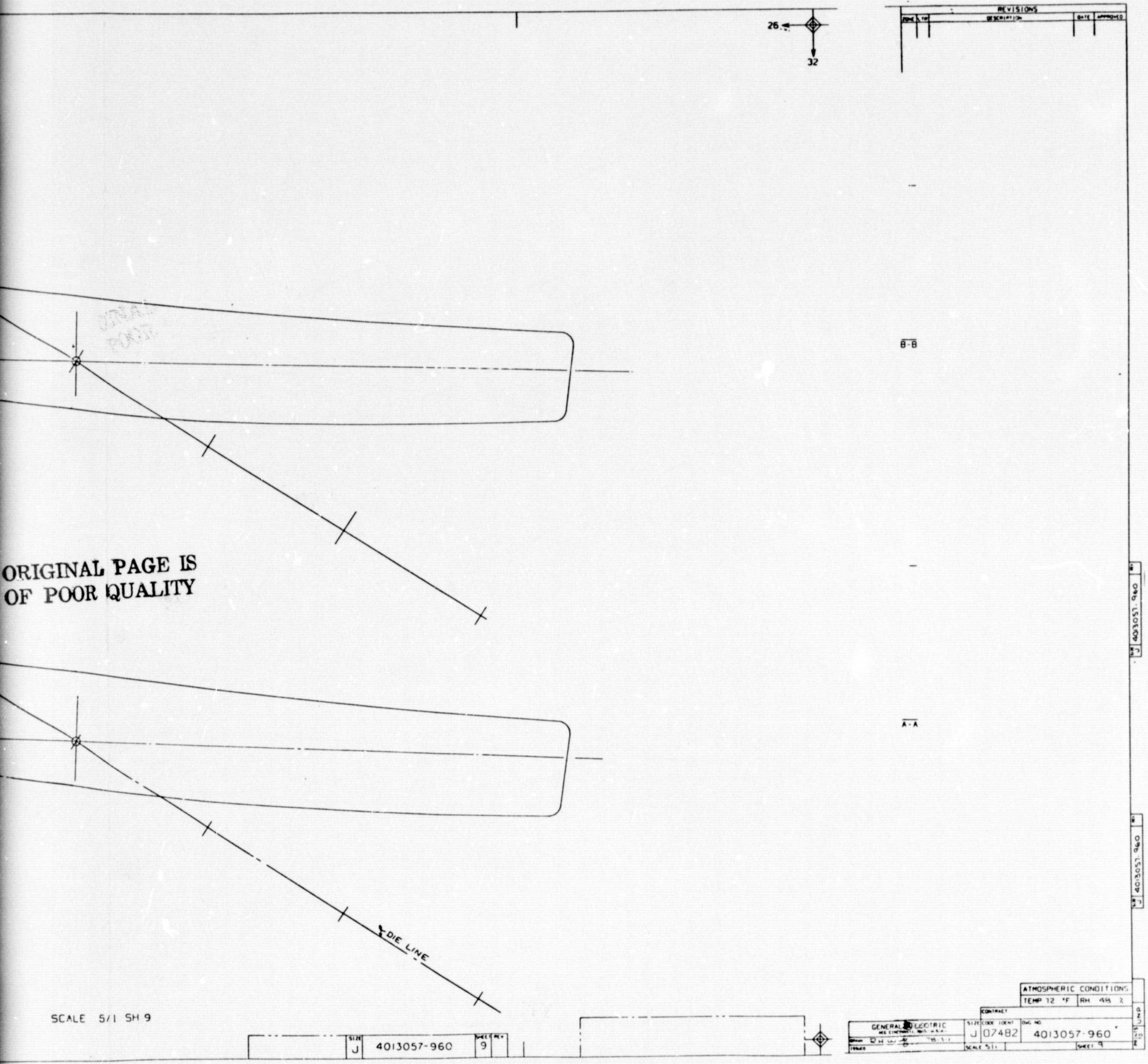


2 INCREMENTAL SPACING OF DIVISIONS ON DIE LINE 1.000

1 PERIODICALLY CHECK TRAMMEL POINTS, PERMISSIBLE VARIATIONS .0002/IN, .005 MAX TOTAL ALLOW FOR ATMOSPHERIC VARIATION FROM THAT STATED HEREON
THERMAL EXPANSION 15X10 * IN/IN/DEGREES F
HUMIDITY EXPANSION 12X10 * IN/IN PERCENT RH

COOR REEL 39993

SCALE 5/1 SH 9



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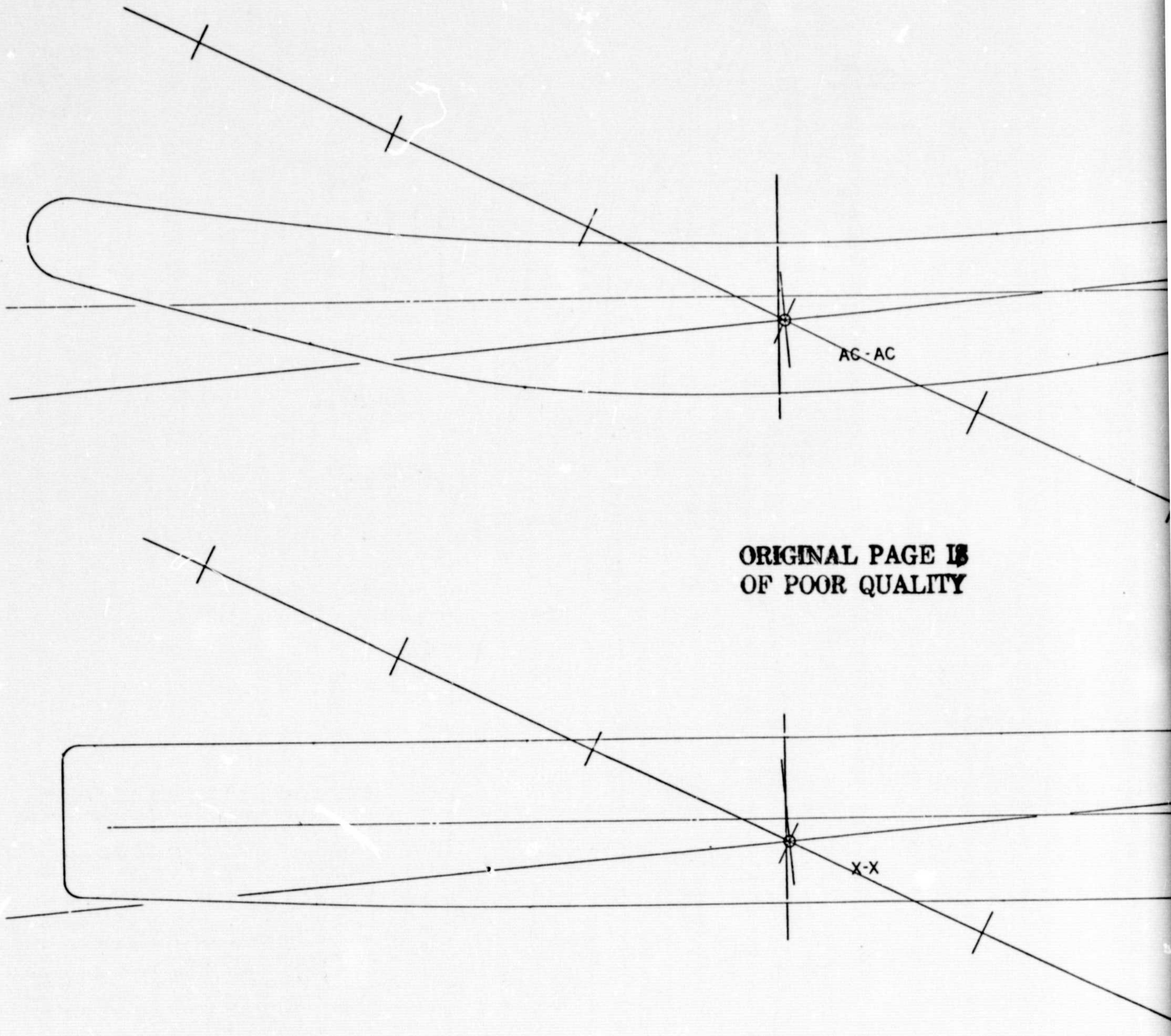

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J 4013057-960 10

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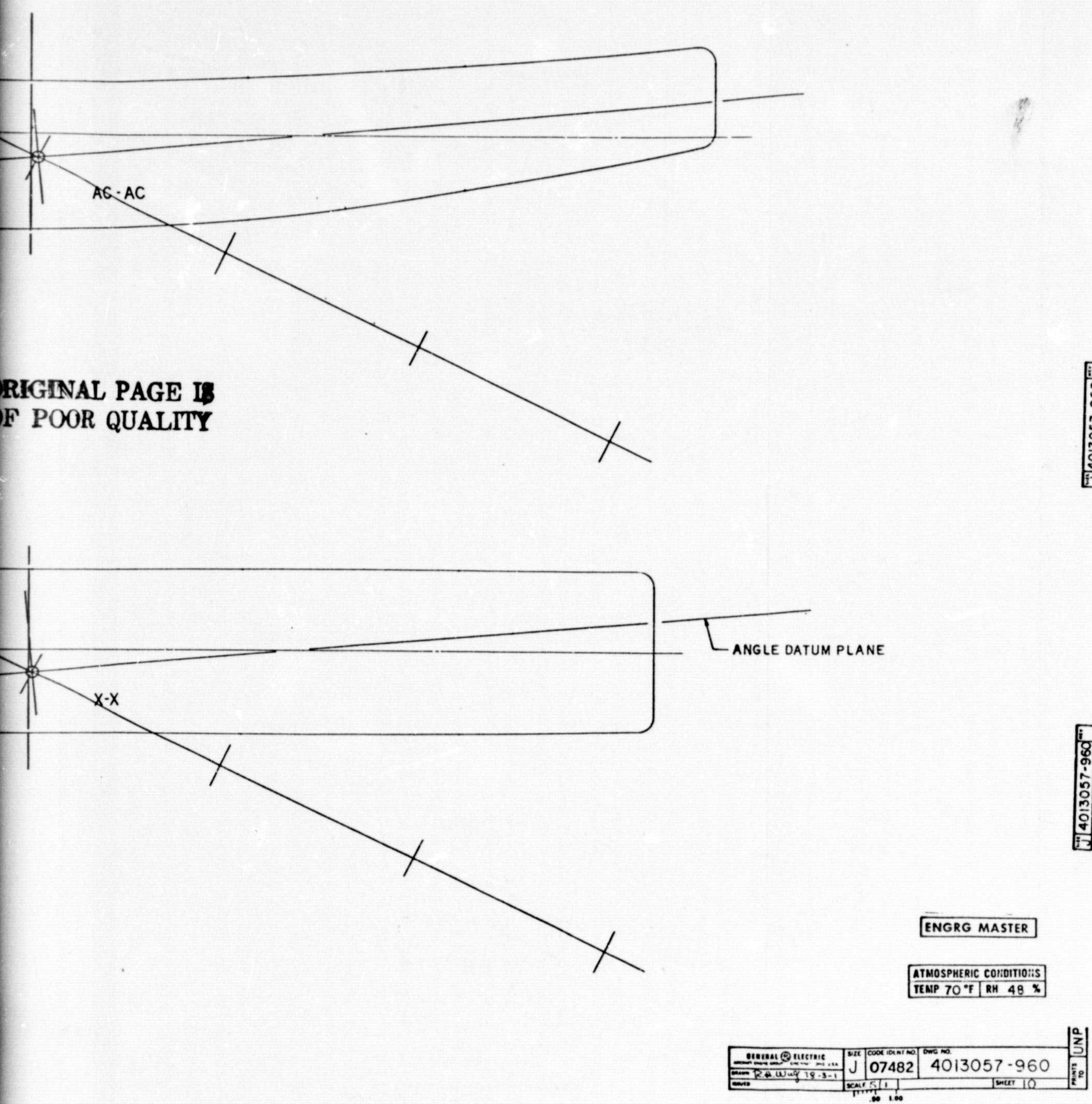

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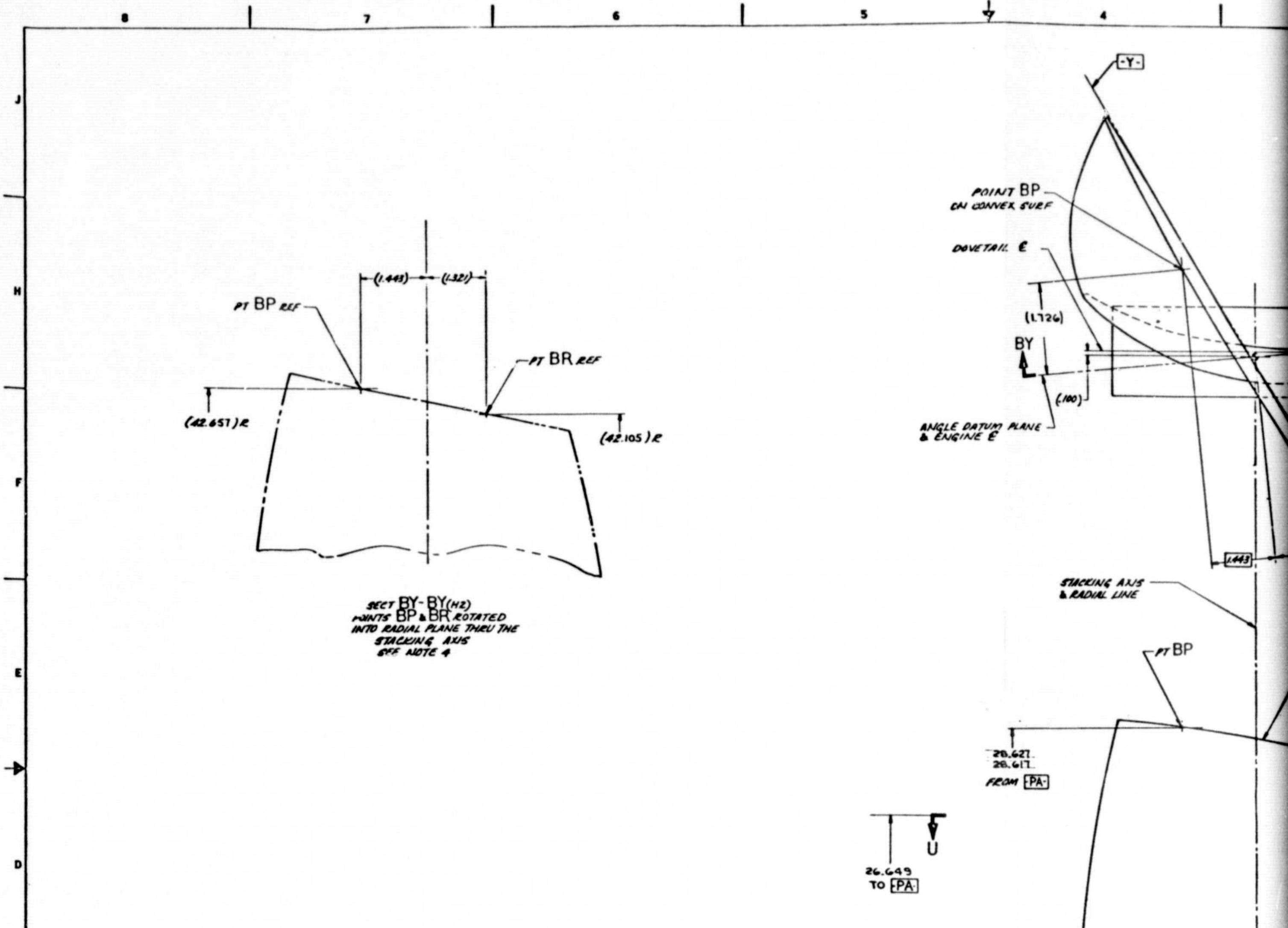

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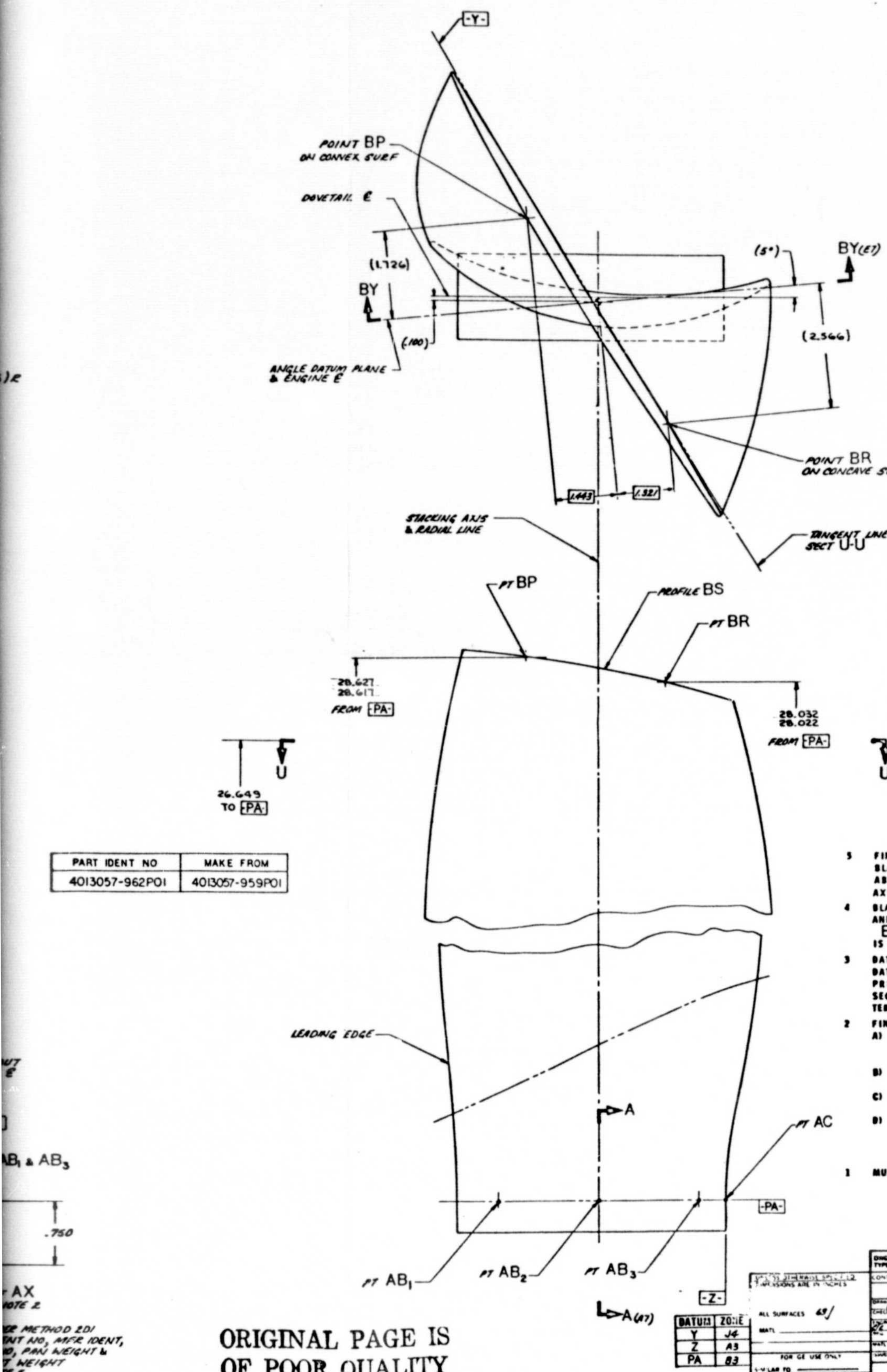

5 FINISHED BLADE TO BE PAN WEIGHED TO THE NEAREST GRAM. BLADE TO BE MOMENT WEIGHED TO THE NEAREST GRAM-INCH ABOUT AN AXIS EQUIVALENT TO ENGINE ℄ & ALSO ABOUT AN AXIS EQUIVALENT TO THE BLADE RADIAL AXIS.

4 BLADE TIP CUT OFF CONTOUR ON WHICH LIE POINT BP (E4) AND POINT BR (E3) IS DEVELOPED FROM PROFILE BS (E3) AS A SURFACE OF REVOLUTION. PROFILE BS IS A STRAIGHT LINE IN SECT BY - BY

3 DATUM SURF AS SHOWN ARE IN THE MACHINED CONDITION. DATUMS ARE AS FOLLOWS:
PRIMARY -PA- ESTABLISHED BY PTS AB_1, AB_2 & AB_3
SECONDARY -Z- ESTABLISHED BY PT AC
TERTIARY -Y- ESTABLISHED BY TANGENT LINE OF SECT U-U

2 FINISHED DOVETAIL REQUIREMENTS:
A) SHANK MUST BLEND SMOOTHLY WITH EXTERNAL LAMINATIONS NO UNDERCUTS OR DELAMINATIONS OF THESE PLYS ARE ALLOWED. NO SHARP CORNERS OR RECESSES ARE PERMITTED
B) DIM AE (B7) MUST NOT VARY MORE THAN .005 AT ANY POINT ALONG THE DOVETAIL LENGTH
C) PRESSURE SURF AV (A7) & AX (A6) MUST BE ⏥ .005 ALONG DOVETAIL LENGTH
D) ENGINEERING MASTER ______ DEFINES THE MAX & MIN CONTOUR OF THE DOVETAIL. AN APPROVED REPRODUCTION ON STABLE FILM MAY BE USED IN THE PRODUCTION & INSPECTION OF THIS CONTOUR

1 MUST CONFORM TO:
P1TF3 CL-A (INTERPRETATION OF DWG)
P1TF9 CL-A (MACHINED FEATURES)
P23TF3 (IDENT MARKING) SEE ZONE A6

DWG TYPE DETAIL

UNLESS OTHERWISE SPEC 12 DIMENSIONS ARE IN INCHES
ALL SURFACES 63/

SIGNATURES	YR-MO-DA
DRAWN	78-3-3
CHECKED	78-3-6
	78-3-6

GENERAL ELECTRIC
AIRCRAFT ENGINE GROUP CINCINNATI, OHIO, U.S.A.

BLADE, FAN-LARGE B/AL
MACHINED FORM

SIZE E | FSCM NO 07482 | DWG NO 4013057-962
SCALE 1/1

5/5
(75)

FOLDOUT FRAME 2

5.0 CONCLUSIONS

A detailed CF6 boron/aluminum blade design has been completed which is projected to be satisfactory for meeting engine operating requirements including aeromechanical and small bird FOD resistance requirements.

6.0 RECOMMENDATIONS

The successful demonstration of the as-designed CF6 boron/aluminum blade presented herein hinges, to a large degree, on the manufacturing quality level of the blades to be fabricated. In order to achieve the quality level needed to successfully demonstrate the structural adequancy and FOD capability of the B/Al blades, the manufacturing process used must be capable of providing properties equivalent to the design allowable used in the design analysis. In addition, localized defects or stress raisers should be avoided, especially in the critical areas of the root transition and the region of localized impact.